Epidemiological and economic simulation of *Salmonella* control in the pork supply chain.

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
prof. dr. ir. L. Speelman,
in het openbaar te verdedigen
op vrijdag 16 januari 2004
des namiddags te vier uur in de Aula.

Epidemiological and economic simulation of *Salmonella* control in the pork supply chain.
PhD-thesis Wageningen University and Applied Research of Animal Sciences Group, Wageningen UR– with references – with summary in Dutch
Van der Gaag, M.A., 2004.
ISBN: 90-5808-973-8

Abstract

Pork can be regarded as an important source for food borne salmonellosis. *Salmonella* bacteria can be introduced and spread in every stage of the pork supply chain and cause a risk for food safety. The objective of this research is to gain insight into the epidemiological and economic effects of different strategies in the finishing, transport, lairage and slaughtering stages to improve the food safety of pork with respect to *Salmonella*. To collect information on possible control measures and on details of the course of infection and contamination, a survey among 75 experts in the Netherlands and Denmark was carried out. Knowledge (both from experts and from literature) about the interaction and relations between the epidemiological and economic aspects was limited. Therefore, two separate models were designed, one for the epidemiological aspects and one for the economic aspects of *Salmonella* control in the pork supply chain. The epidemiological model to simulate the introduction and spread of Salmonella in the pork supply chain is a detailed stochastic state transition model. The economic model is a deterministic simulation model. For each control measure in the finishing to slaughtering stages, the costs and revenues have been calculated using the technique of partial budgeting. Since it is not feasible in practice to implement all possible control measures, for each stage a package of measures has been defined by selecting feasible measures. The net costs for these packages per stage were calculated per pig. In the finishing stage, the net costs for the control package are € 2.99, for the transportation stage € 0.65, for the lairage € 0.40 and for the slaughtering stage € 1.47. Combining the results of the epidemiological and the economic models allowed comparison of the cost-effectiveness of different control strategies for *Salmonella* in the pork supply chain. The research has revealed the importance of a chain approach instead of considering each stage individually. The effectiveness of *Salmonella* reduction depends on the efforts of all participants in a stage. A small number of poorly performing participants can disproportionately reduce the effectiveness of the efforts of the other participants. A payment system based on the *Salmonella* prevalence of the supplied animals or carcasses is a promising strategy to improve food safety. Strategic management principles have been applied to define aspects that are important for the design and implementation of a *Salmonella* control program in the entire pork supply chain. Two possible control programmes are described: a Food Safety Program and a Competitive Program.

Aan mijn opa Geert Bisschop

Contents

Chapter 1

General Introduction

1 Introduction

In general, consumers in developed and prosperous countries take an interest in the way their food is produced. Besides environmental issues and animal welfare that are considered important, consumers do not want to run any health risk by consuming food. Recently their concerns have been increased by food safety incidents. Examples are Bovine Spongiform Encephalopathy in cattle (Collinge, 1999), outbreaks of human salmonellosis traced back to the consumption of poultry and pork (Wegener and Baggesen, 1996; Van Pelt and Valkenburgh, 2001), listeriosis caused by pâté products (De Valk et al., 2001) and dioxin scraps in animal feed and meat (Bernard et al., 2002).

There are three categories of food safety risks: chemical risks, physical risks and microbiological risks. The latter one causes the highest incidence of food borne illness. Microbiological contamination can originate from the live product (animal or plant) or from cross-contamination at pre-harvest and post-harvest. Many micro-organisms are ubiquitous in nature, consequently pathogenic micro-organisms can enter the supply chain in many stages. Therefore, the entire supply chain has to be involved in controlling most microbiological risks (Berends et al., 1998; Lammerding and Fazil, 2000). Micro-organisms thrive best in a high protein, non-acid environment such as meat which makes meat and this makes meat a serious risk for food borne illness. In general, the bacteria *Salmonella* and *Campylobacter* cause most food borne illness, which results in high societal costs such as reduced productivity, treatment, hospitalisation and premature death. For human salmonellosis in the Netherlands, these costs are estimated to be between 32 and 90 million Euro per year (van Pelt and Valkenburgh, 2001). Since one out of four cases of human salmonellosis is caused by a serotype occurring in pigs, pork can be regarded as an important source of food borne salmonellosis (van Pelt and Valkenburgh, 2001).

2 *Salmonella* in the pork supply chain

The pork supply chain is a whole of stages that all contribute to produce pork for the consumer. Figure 1 presents the main stages in the pork chain. Pork is produced and processed in the stages from breeding through consumer, the other stages are facilitating stages for the production stages. To improve the food safety of pork with respect to *Salmonella*, the focus should be on the reduction of contamination of carcasses, since the carcass is the basic end-product of the pork supply chain. Therefore, the research in the thesis has concentrated on the production stages and in particular on the stages multiplying, finishing, transport, lairage and slaughtering. These stages produce the basic pork product from piglet to carcass.

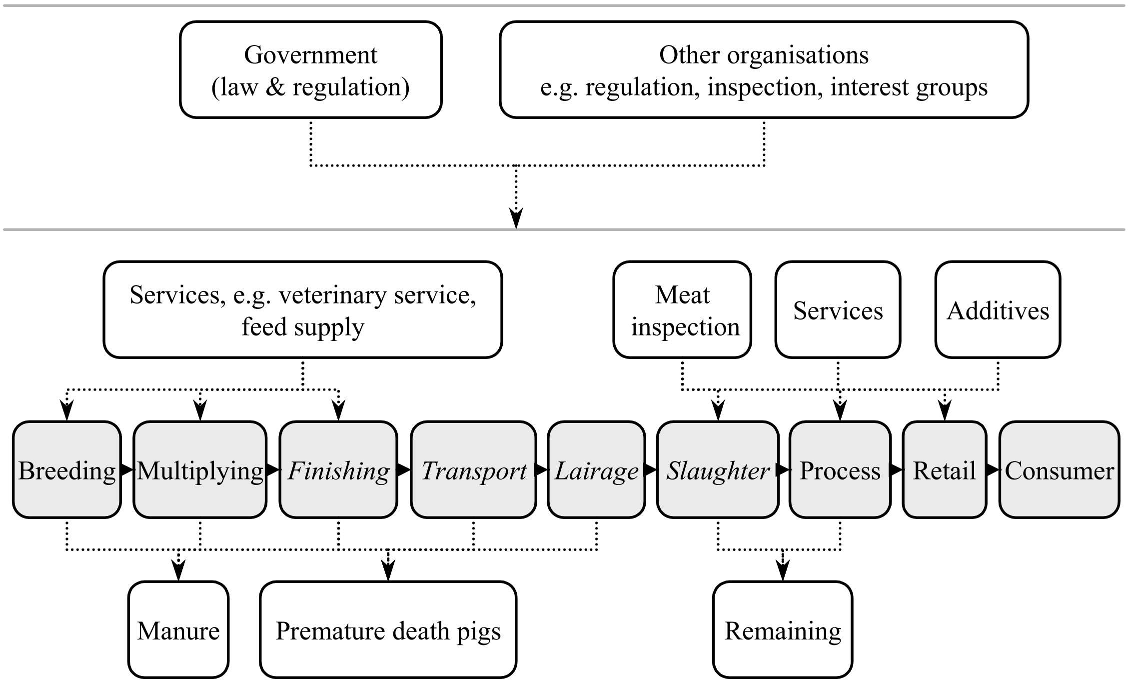

Figure 1 Production stages and the major facilitating stages of the pork supply chain (stages printed in *Italic* are included in detail in this thesis; it should be noted that transportation also occurs between other stages than only finishing and lairage)

Until now, over 2000 types of *Salmonella* have been identified and all of them are potentially pathogenic (Carter et al., 1995). Not all types occur in the Netherlands. Because of the ubiquity of the bacteria, it is unlikely that zero prevalence in the pork supply chain can be reached and maintained. In literature, risk factors regarding the presence of *Salmonella* and control strategies in separate stages in the pork chain are described. An entire chain approach however, is scarce. It is remarkable that most of these studies lack any economic evaluation, calculations have only been carried out for the societal costs of food borne illness.

Strict national and international regulations for food production are implemented and are under development (Anonymous, 2001). However, before decision-makers will issue regulations or specific measures, the cost-effectiveness of these regulations should be determined. It has to be avoided that expensive but not effective regulations are put into practice. Besides, since there is interaction between the stages in the supply chain, it is also essential to determine the stage in which cost-effectiveness of measures is at its highest. In short, for sound decision making better understanding of the dynamics and control of *Salmonella* in the pork supply chain and the economic consequences of control are needed.

3 Research Objectives

The main objective of this research is to gain insight into the epidemiological and economic effects of different strategies to improve the food safety of pork with respect to *Salmonella*. As already mentioned, the basis of all pork products for the consumer is a chilled carcass at the slaughterhouse. The focus of the research has been on the pork supply chain from piglet to carcass. To achieve the objective, the cost-effectiveness of control measures and strategies should be estimated. In order to carry out these estimations, insight in the effect of control on the spread of *Salmonella* and the costs for control is needed as a basis. The main objective was divided into the following four sub-objectives:

1. Exploration of possible measures that can be implemented in the pork supply chain to control the introduction and reduce the prevalence of *Salmonella* in the end product;
2. Development of two computer models; an epidemiological model to simulate the introduction and spread of *Salmonella* in the pork supply chain and an economic model to evaluate the economic consequences of control measures in the pork supply chain;
3. Obtaining insight into the cost-effectiveness of preventive and corrective measures and strategies to control *Salmonella* in stages of the pork supply chain;
4. Formulation of promising strategies in the pork supply chain with respect to control of *Salmonella*.

4 Outline of the thesis

The sub-objectives were the guide for the outline of the thesis, which is presented in Figure 2.

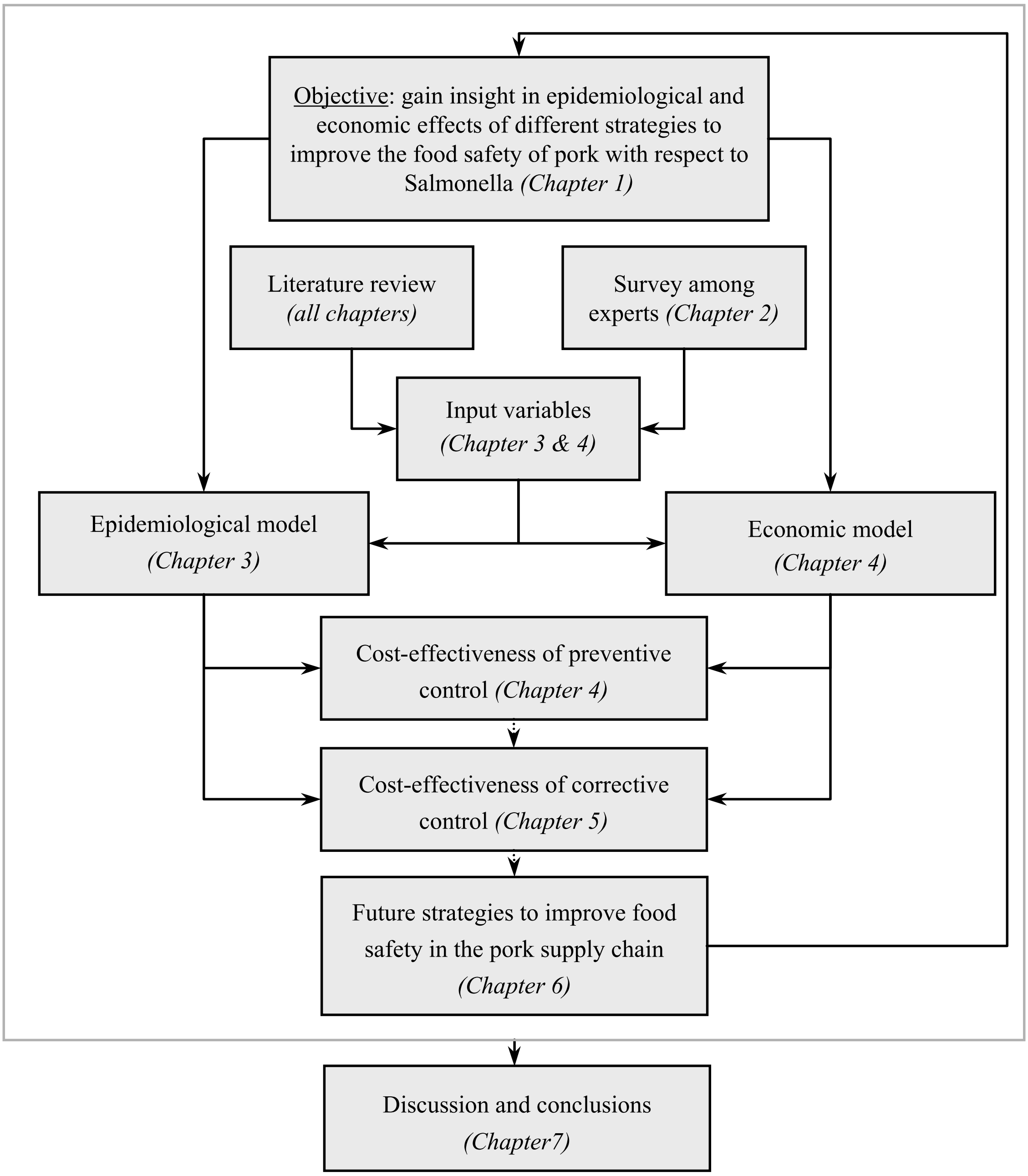

Figure 2 Outline of the thesis

Chapter 2 deals with the first sub-objective to explore the possible measures to control introduction and reduce the prevalence of *Salmonella* in the end product. By conducting a survey in the Netherlands and Denmark, the main control measures in each stage of the pork supply chain and insight in the infection dynamics of *Salmonella* were obtained (Chapter 2). With this information and a literature review, the second sub-objective was carried out: designing two computer models; an epidemiological model to simulate the introduction and spread of *Salmonella* in the pork supply chain (Chapter 3) and an economic model to evaluate the economic consequences of control measures (Chapter 4).

The third sub-objective was to obtain insight into the cost-effectiveness of preventive and corrective measures and strategies to control *Salmonella* in stages of the pork supply chain. The models were used for simulation experiments and the results of the epidemiological and the economic models were combined in the comparison of the cost-effectiveness of different control strategies to control *Salmonella* in stages of the pork supply chain (Chapter 4 and 5). However, the choice for a control programme does not only depend on the cost-effectiveness. This is elucidated in Chapter 6, where the fourth and final sub-objective of the research is described. Strategic management principles have been applied to define the aspects that are important for the design and implementation of a *Salmonella* control programme in a pork supply chain (Chapter 6) such as choosing appropriate monitoring and testing procedures. The General Discussion (Chapter 7) discusses the research approach, gives an example of a practical implication and presents the main conclusions of the thesis.

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Chapter 2

Elicitation of expert knowledge on ccontrolling Salmonella in the pork chain

Abstract

Salmonella is one of the most important risks for food safety, while pork is one of the sources of human salmonellosis. A chain approach is essential to reduce Salmonella in pork products. A survey was carried out with Dutch and Danish experts in the field of Salmonella to evaluate the entire pork supply chain. The aims of the survey were to determine and rank possible management interventions (such as adjusted or new procedures, technical adjustments and control measures), and to estimate the details of the course of infection and contamination. An additional objective was to compare the opinions from experts from different countries and with a different background. The stages that were expected to be most effective to improve food safety with respect to Salmonella in pork by implementing management interventions were the stages finishing (by preventing the spread of Salmonella within the farm) and slaughtering (by preventing cross-contamination). The differences in the opinions of respondents from different backgrounds were mainly reflected by the relative importance of specific management interventions. For instance, the Danish respondents attached more importance to the purchase of Salmonella free piglets in the finishing stage and to logistic slaughter. Respondents with a research background seemed to attach most importance to interventions that were also presented in recent literature, such as feeding non-heated grain to finishing pigs. For issues in which multiple stages of a supply chain are involved, a solid basic knowledge about the conditions per stage with respect to the issue is necessary.

1 Introduction

A supply chain consists of stages that fulfil, directly or indirectly, customer requests and each stage of the supply chain performs different processes and interacts with other stages of the supply chain (Chopra and Meindl, 2001). A major issue in food supply chains is ensuring food safety. Food safety risks can be chemical, physical or microbiological, the latter being the most important one. The bacteria *Salmonella* and *Campylobacter* are the major agents for bacterial foodborne zoonoses, while zoonoses are diseases that can be transferred from animals to humans. In the Netherlands, 25% of the annual 50,000 human cases of salmonellosis are caused by serotypes that occur in pigs (Van Pelt and Valkenburgh, 2001). Over 90% of the pig farms had pigs that were serologically positive for *Salmonella* (Van der Wolf, 2000), so it is very likely that every Dutch slaughterhouse will receive contaminated pigs. At the slaughterhouse, the average prevalence of contaminated carcasses is estimated at about 2% (Swanenburg, 2000). In 2000 18.8 million pigs were slaughtered in the Netherlands (Anonymous, 2001), which indicates that in 2000 over 350,000 contaminated carcasses entered the food chain.

Concerning food safety issues like *Salmonella* contamination which can occur in each stage of the supply chain, all participants have to be involved (e.g. Berends et al., 1998; Lammerding and Fazil, 2000). One stage cannot solve the food safety risk of pork with respect to *Salmonella*. And what is more, the EU approach is to take the necessary preventive interventions at all the appropriate stages in the supply chain during production and processing in order to avoid contamination (Anonymous, 1997). Besides the shortage of compiled knowledge of possible management interventions in the entire pork supply chain, there is a lack of knowledge about the course of infection and contamination. To overcome these shortcomings, a survey was carried out with experts in the field of *Salmonella* covering the entire pork supply chain.

The first aim of the survey with experts was to determine and rank management interventions to reduce introduction and spread of *Salmonella* in the pork supply chain. The second aim was to compare the opinions from experts from different countries and with a different background in order to get insight into the extent of agreement. This insight may play a role in the future control of *Salmonella* in the pork supply chain and in the preferable co-operations between stages in the chain to improve public health.

The outline of the paper is as follows: section 2 background about the pork supply chain is described. Section 3 is concentrated on the design of the survey, and section 4 on the way of analysis. Section 5 presents the results about management interventions in the pork chain. Section 6 presents the results about the course of infection and contamination and section 7 provides the conclusions and discussion.

2 The pork supply chain

2.1 Introduction on the pork supply chain

Within an expanding market, production and efficiency in food supply chains increased through specialisation and concentration. In the pork supply chain primary farms are highly specialised in multiplying or finishing to maximise the product output. The number of primary farms halved the last decade from 29,000 pig farms in 1990 to 14,500 pig farms in 2000 although the number of pigs decreased only with 6% from 13,9 million to 13,1 million pigs (CBS, 2002). Nowadays markets have become saturated and firms in the post harvest stages of the pork supply chain are merging to survive in a market with global competition. To subsist it is important to offer a differentiated package of products to retail and consumer. For specific market and production characteristics, such as assuring food safety in the supply chain, joint investments and co-operation among stages are needed (Ziggers and Trienekens, 1999). Enforcing the implementation of performance and process standards to assure e.g. food safety are increasingly related to meta-management systems at all levels of a chain (Reardon and Farina, 2002). It is unlikely that a supply chain will operate effectively unless all participants are able to identify value both to themselves and to their customers (Christopherson and Coath, 2002). Especially with food safety issues like *Salmonella* contamination which can occur in each stage of the supply chain all participants have to be involved. In any case, before putting all kinds of management interventions and rules into practice, more insight is needed into what interventions are (expected to be) the most effective to improve food safety of pork with respect to *Salmonella.* It is not possible to test all management interventions on a large scale in field studies, since such field studies are too costly and some interventions have not been applied yet in practice (Dijkhuizen and Morris, 1997). In the literature the focus is mostly on one single stage in the chain (e.g. Stege et al., 2001; Isaacson, 1999a,b; Davies and Wray, 1997) or on one single aspect of *Salmonella* (e.g. Jørgensen et al., 1999; Van Winsen, 2001). So, partial information on *Salmonella* is available, but a complete chain approach is lacking.

2.2 Salmonella in the pork supply chain

Salmonella is ubiquitous in nature and as stated before, it can be introduced and spread in each stage of the pork chain. Pigs can introduce the bacteria from the former stage or by external sources, such as people, rodents, feed, water, et cetera. Once introduced, the bacteria can be spread in the farm or firm and go via the entire pork chain to the consumer. A certified *Salmonella*-free meat product is hard to attain (decontamination of meat is not allowed in the European Union), but a certified production process to prevent *Salmonella* is an effective strategy to fulfil the customers' request/demands.

To clarify the pork supply chain, this chain will be described briefly. The pork supply chain consists of several stages. Figure 1 shows the different stages in the chain: breeding, multiplying, finishing, transportation, slaughtering (lairage and slaughter), processing, retailing and consuming. All stages have relations with partners that are linked to the main food supply chain, such as feed companies and service suppliers. The possible management interventions of the stages multiplying through slaughter are discussed separately in the survey. These stages produce the basic end product of the pork chain, which is a chilled carcass.

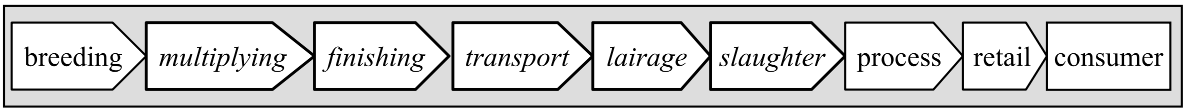

Figure 1 Schematic structure of the pork supply chain. The stages written in *Italic* script are discussed separately in the survey.

The primary stages (breeding through finishing) are for the larger part specialised family farms. The breeding stage produces sows for the multiplying stage. In the multiplying stage finishing pigs are produced, these pigs are sold to the finishing stage at an average live weight of 25 kilograms. Multiplying and finishing may be on the same farm. In the finishing stage pigs are fattened to a live weight of approximately 110 kilograms. Specialised private transport companies in the transportation stage arrange the transportation of the pigs from the finishing farm to the slaughterhouse. At the slaughterhouses, pigs stay in the lairage (holding pens) for a few hours for calming down after the transport. At the slaughtering stage pigs are slaughtered. The next day the carcass is processed further and transported to retailers, from where it is sold to the consumer.

3 The design of the survey

In this research, an expert was defined as someone who is involved in the pork supply chain and is known for his/her knowledge about *Salmonella* in pigs and/or pork. Therefore a list was formulated with experts in the Netherlands and Denmark. People on the list were asked whether they knew other people that are known for their knowledge about *Salmonella*. The design of the Danish pork supply chain is more or less similar to the Dutch situation. Moreover, Denmark has had a surveillance and control program for *Salmonella* since 1995 (Alban et al., 2002).

The recommendations by Summerhill and Taylor (1992) were followed as to designing and distributing the survey. In total 80 experts were invited to participate in the survey; 48 from the Netherlands in March 2001 and 32 from Denmark in July 2001. Two weeks after the invitation, the surveys were sent to 75 experts who were willing to completing a survey. After 3 to 4 weeks a reminder was sent.

The survey consisted of five parts, categorised in Table 1 and described in detail in the next section.

Table 1 The five parts of the survey

Part	Subject	Motivation	Response possibilities
A	General	Categorise respondents	Country and background
B	Management interventions	Ranking interventions	Distribution of 100 points
C	Statements	Compare categories of respondents	Agree / Not agree / Do not know
D	Course of infection	Compare categories of respondents	Three point estimation
E	Course of contamination	Compare categories of respondents	Three point estimation

The five parts of the survey:

A) General; Questions related to the background and the field of knowledge of the respondent.

B) Management interventions; Questions related to the (relative) importance of management interventions per stage. The stages multiplying, finishing, transportation, lairage and slaughterline were discussed separately. For each stage ten to fifteen management interventions were given based on articles in literature that concerned details of the pork supply chain (e.g. Stege et al., 2001; Isaacson, 1999a,b; Davies and Wray, 1997; Jørgensen et al., 1999; Van Winsen, 2001). The categories of management interventions are described in Tables 3 to 7 in section 5. Respondents could add additional interventions. The respondents were asked to distribute 100 points over the interventions to indicate the (relative) importance of each individual intervention.

C) Statements; 26 statements as to *Salmonella* in the pork supply chain were formulated (see Appendix). Some statements were included to test the consistency of the respondent (to test whether their answers to these statements corresponded with their answers given in parts D and E). The respondent was asked to indicate whether (s)he agreed with the statement or not. Twenty-six statements were presented to the Dutch respondents and a selection of twelve statements was presented to the Danish respondents. After conducting the Dutch survey, respondents indicated that some statements were too obvious and decreased the motivation to complete all statements. Therefore, a selection was made for the Danish survey.

D) Course of infection in finishing pigs First, an infected pig was defined as a pig that had been in contact with such a dose of *Salmonella* bacteria that the pig becomes infectious i.e. starts shedding *Salmonella* itself. Eight variables about the course of infection were included in part D and for each variable a three-point estimation was asked, in other words the respondent estimated the minimum value, most likely value and maximum value for each variable. The eight variables were:

- D1 duration of seroconversion period
- D2 duration of infectious period; pig is serologically negative and fed dry-pelleted feed
- D3 duration of infectious period; pig is serologically negative and fed acidified feed
- D4 duration of infectious period; pig is serologically positive and fed dry-pelleted feed
- D5 duration of carrier period
- D6 period to become serologically negative after having become positive
- D7 infection rate in a group of 100 serologically negative pigs
- D8 infection rate in a group of 100 serologically positive pigs.

E) Course of contamination of carcasses at the slaughterline. For the importance of contamination at the slaughterline a three-point estimation was asked for four variables, whereas for each variable a three-point estimation was asked. The four variables were:

- E1 probability that a bacteria-free carcass ends up contaminated, if one of the preceding carcasses is contaminated with *Salmonella*
- E2 probability that a bacteria-free carcasses ends up contaminated if four preceding carcasses are contaminated
- E3 probability that an infected pig ending up as a bacteria-free carcass

- E4 probability that a bacteria-free pig ending up as a contaminated carcass if half the pigs slaughtered that day are contaminated.

4 Analysis

The respondents were classified by country of origin (the Netherlands and Denmark) and by background (Animal production, Retail & Policy and Research). In the class "Animal production" respondents working for slaughterhouses, feed industry and people from (organised) interest groups were included, in the class "Retail & Policy" respondents working for retail, government and product boards were included and respondents working for research institutes and universities were in the class "Research".

The management interventions were classified per stage into five to seven categories. The Kruskal Wallis test was used to test the difference in specific interventions and categories of interventions between groups of respondents. Per statement the percentage of respondents who agreed was computed and the differences between groups of respondents were calculated. For all three-point estimations of the 12 variables, the mean and standard deviations were calculated per group.

The response rate was 59%. Seven percent of the respondents indicated they did not want to complete the survey. Reasons for this were that they did not have the specific knowledge, they were not interested or they could not find time because of the outbreak of Foot-and-Mouth Disease in the Netherlands. In total 39 experts sent in the survey (Table 2).

Table 2 Number of respondents per country and background

	The Netherlands	Denmark	Total
Animal production	8	2	10
Retail & Policy	7	4	11
Research	8	10	18
Total	23	16	39

A response rate of over 50% is fairly good for a mail survey. Some questions were not or incompletely answered, which is not unusual. Most respondents who did not or incompletely answered a question indicated that they did not have the knowledge to answer the question. Maybe the survey was too long for some respondents; completing it took about one hour.

It was not possible to test differences between groups of respondents for the statements and the three-way estimations, since only one or a few respondents answered these questions.

5 Results Management interventions in the Pork Chain

5.1 Multiplying and finishing: management interventions and statements

In the multiplying stage, the emphasis was on the prevalence of *Salmonella* in piglets of 25 kilograms while in the finishing stage the emphasis was on the prevalence of *Salmonella* in finishing pigs of 110 kg.

Table 3a Distribution of 100 points over management interventions in the multiplying stage

Interventions related to:	Total N=34	NL n=20	DK n=14	Animal prod. n=10	Retail & policy n=10	Research n=14
Feed	46	41	52	35	50	51
Hygiene related with spread	16	19	13	19	13	16
Salmonella-free sows	14	13	16	15	17	13
Hygiene related with introduction	13	17*	8*	16	11	12
Housing sows and piglets	10	9	11	15	9	8
Other	2	2	0	1	0	1
Total	100	100	100	100	100	100

Table 3b Distribution of 100 points over management interventions in the finishing stage

Interventions related to:	Total N=34	NL n=20	DK n=14	Animal prod. n=9	Retail & policy n=8	Research n=17
Feed	38	33	46	31	32	45
Hygiene related with spread	24	28	19	29	24	22
Salmonella-free piglets	15	12*	20*	13	13	18
Hygiene related with introduction	8	9	6	9	7	7
Management[1)]	8	10	6	8	13	6
Other	5	8*	1*	4	12*	2*
Batch production	2	1	2	6	0	0
Total	100	100	100	100	100	100

1) E.g. climate control, strict protocol for visitors
* p<0.05

As shown in Table 3, the most important category of management interventions was related to feed supply. In particular, the use of acidified or fermented feed and buying certified *Salmonella*-free feed were mentioned. Whereas 43% of the Danish respondents also indicated that meal feed and non-heated grain were effective management interventions, none of the Dutch respondents did so. From the survey it did not become clear whether the feeding interventions in the multiplying stage should be applied to piglets, sows or both. The second category of interventions was related to hygiene to prevent spread of *Salmonella* on the farm. The interventions mentioned were: using separate materials such as brooms and boots per barn or compartment, cleaning and disinfecting compartments for piglets after each period and separate housing facilities for sows and weaned piglets. Implementing a new feeding strategy and separate housing facilities concern only the multiplying stage. Purchase of certified *Salmonella* free sows has also an effect on the management of the former stage (breeding) and information exchange is essential.

There was a significant difference between the Netherlands and Denmark in the category hygiene related to introduction in the multiplying stage. The Danish respondents attached more importance to purchasing *Salmonella*-free piglets in the finishing stage. There were no significant differences among the respondents from different backgrounds.
Seven statements concerned the primary stages. The percentages of respondents who agreed are shown in Table 4. A part of the 12 statements for all respondents was linked with an analytical model (an epidemiological framework) about the course of a *Salmonella* infection in live pigs. This model is shown in Figure 2.

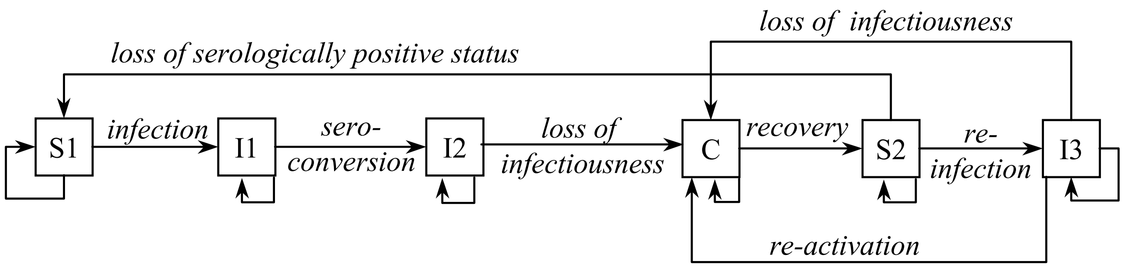

Figure 2 Course of a *Salmonella* infection in live pigs (S = susceptible, I = infectious and C = carrier)

The model starts with a *Salmonella*-free pig (S1). If the pig becomes infected, it becomes infectious (I1) and after a while serologically positive (I2). As soon as the pig stops shedding (so it is not infectious anymore) it can still carry bacteria in the intestines or lymphatic system, the so-called carrier stage (C). A carrier can become infectious again

(I3) or become bacteriologically *Salmonella*-free, but remains serologically positive (S2). From state S2 the pig can become re-infected (I3) or become serologically negative (S1).

Table 4 Percentage of respondents who agreed with the statements with respect to primary stages, when the 'do not know' answers are left out

Statement	% agreed
The course of a *Salmonella* infection can be represented as in Figure 2.	92*
Salmonella infections do not influence the production results of finishing pigs.	71
After the infectious period a pig remains (temporarily) carrier, e.g. in intestines or lymph nodes.	97
After the carrier period a pig remains (temporarily) serologically positive.	83*
Sensitivity to *Salmonella* does not depend on race, weight or sex.	64
After a pig having gone through an infection, it is less sensitive to a new *Salmonella* infection.	77*
The infectivity of infectious pigs is about equal in states I1, I2 and I3.	30*

* Over 25% of the respondents indicated 'do not know'

For two statements there was a difference ($p<0.05$) among respondents with a different background. Over 80% of the respondents from Research and Retail & Policy agreed that *Salmonella* does not effect the production results, whereas only 40% of the respondents from Animal production agreed with this statement. This difference in perception is important for the willingness to invest in interventions and for introduction of new regulations. Policymakers may not realise which side effects occur related to food safety issues in the primary stages. If participants in the primary stages expect that higher prevalence of *Salmonella* at the farm leads to a decrease in production performance the willingness to invest may be higher than in case they do not expect a decrease in performance. This argument should result in an increase in willingness to invest. The statement that the sensitivity to *Salmonella* does not depend on race, weight or sex includes three assumptions. About 57% of respondents from Animal production and from Retail & Policy agreed, whereas 80% of the respondents from Research agreed. The respondents who did not agree indicated that they only did not agree with the assumption concerning weight (which is correlated to age). Pigs with a lower weight (i.e. younger pigs) are expected to be more sensitive to *Salmonella* infection than heavier (i.e. older) pigs.

The Dutch and Danish responses differed for two statements. All Danish respondents agreed on the statement that 'After a pig having gone through an infection, it is less sensitive to a new *Salmonella* infection', and only 25% of the Dutch respondents agreed. The percentage of agreement for the statement 'The infectivity of infectious pigs is about equal in states I1, I2 and I3' was also higher among the Danish respondents (38%) than among the Dutch respondents (14%).

5.2 Management interventions during transportation

The results of the distribution of 100 points over the management interventions are given in Table 5.

Table 5 Distribution of 100 points over management interventions in the transportation stage

Interventions related to:	Total N=33	NL n=21	DK n=12	Animal prod. n=10	Retail & Policy n=7	Research n=16
Logistic transport	21	22	20	25*	13*	22
Hygiene truck	18	16	22	18	22	16
One compartment / ride	17	17	18	15	21	17
Fasting before transport	10	11	7	15*	12	6*
Duration transport over 2 hours	10	9	12	8	6	13
Smooth sides truck	9	10	7	7	9	11
Quiet driving	9	11	6	8	11	9
Other	5	4	7	5	6	6
Total	100	100	100	100	100	100

*: $p<0.05$

The three best interventions to reduce *Salmonella* introduction and spread during transportation according to the respondents were so-called "logistic transport", good hygiene, such as cleaning and disinfecting thoroughly after each ride, and transporting pigs from only one compartment of the finishing farm in one truck. In current practice, pigs from different pens and compartments are put together in one truck. Logistic transport means that trucks are only allowed to transport pigs from finishing farms with the same *Salmonella* status. So there can be specific trucks that may transport pigs from *Salmonella*-free farms. These interventions may have a drastic impact on the current operating procedures. Interventions that can be realised more easily are more patience during loading of pigs into the truck, quiet driving to the slaughterhouse to reduce stress and fasting before transportation. Fasting is advised in most countries, since full intestines may pose a higher risk of puncturing during evisceration (e.g. Borch et al., 1996).

Respondents from Animal production attached more importance to logistic transport than respondents from Retail & Policy, they also attached more importance to fasting before transportation than respondents from Research ($p<0.05$). There were no significant differences between respondents from the Netherlands and Denmark.

There was one statement on transportation: ‘All carrier animals become infectious during transportation (i.e. start shedding).’ In total 14% of the respondents agreed on this statement. None of the respondents from Research agreed. They estimated that 35 to 60% of the carriers would become infectious during transport, depending on the way of loading and the driving style of the driver.

5.3 Management interventions in the lairage

In the lairage, pigs from different finishing farms are collected in compartments of 20 tot 60 pigs each. The lairage is considered a risk factor for *Salmonella* infection and contamination, because pigs from different farms are collected together and the rough floors are hard to clean completely (Swanenburg, 2000; Rostagno et al., 2001). The first management interventions according to the respondents are good hygiene, such as cleaning and disinfecting more frequently, using a construction that can be cleaned better and rodent control. The second management intervention is logistic supply, which means that pigs from *Salmonella*-free herds are not delivered at the same time as pigs from herds with another *Salmonella* prevalence. So pigs from *Salmonella*-free herds or from herds with a low prevalence are slaughtered on specific days or at the beginning of the day. The third, fourth and fifth management interventions were considered more or less equally important (see Table 6).

Respondents from Research attached more importance to a shorter duration in the lairage than respondents from Animal production ($p<0.05$) did. There were no significant differences between respondents from the Netherlands and Denmark.

Table 6 Distribution of 100 points over management interventions in the lairage

Interventions related to:	Total N=32	NL n=20	DK n=12	Animal prod. n=10	Retail & policy n=6	Research n=16
Hygiene lairage	29	30	27	30	31	28
Logistic slaughter	28	26	31	30	18	27
One group per compartment	13	13	13	15	13	11
Closed compartment fences	12	15	9	16	13	10
Shorter waiting period	10	7	14	3*	10	14*
Slatted floors	4	4	3	4	4	3
Other	4	5	3	2	1	7
Total	100	100	100	100	100	100

*: $p<0.05$

The only statement as to lairage was ‘The more infectious pigs in the lairage, the higher the infection risk to *Salmonella*-free pigs’. Almost all respondents (97%) agreed with this statement.

5.4 Management interventions at the slaughterline

According to the respondents, by far the most important management intervention for *Salmonella* at the slaughterline is logistic slaughter. Several conditions have to be met for functional logistic slaughtering: a reliable monitoring system, farms with flexible delivery-strategies, clear transportation planning for delivering pigs and effective cleaning and disinfecting of trucks, lairage and slaughterline. If one or more of these conditions are not met, the effect of logistic slaughter will be limited. So the co-operation of all stages is essential. The second best management intervention was considered decontamination of the carcass at the end of the slaughterline. The European Committee is concerned about using such methods, which should not be applied to restore safety in a product that has been produced under poor hygiene conditions (Frerichs and Venturini, 2002).

Comparing respondents from the Netherlands and Denmark, the Danish respondents attached more importance to logistic slaughter and no splitting of head and throat ($p<0.05$). The Dutch respondents attached more importance to additional cleaning of machines at the slaughterline. The Danish respondents often indicated that the scalding tank should be at least at 62ºC.

The respondents from Retail and Policy attached more importance to careful evisceration than the respondents from Animal production and Research ($p<0.05$).

Table 7 Distribution of 100 points over management interventions at the slaughterline

Interventions related to:	Total N=30	NL n=28	DK n=12	Animal prod. n=7	Retail & Policy n=10	Research n=13
Logistic slaughter	24	20*	31*	29	22	25
Decontamination	15	16	13	19	13	14
Extended cleaning and disinfecting twice a day	14	13	15	11	15	14
Careful evisceration	12	14	9	9*	17*	10
Rectum packing	9	8	10	7	8	10
No splitting head and throat	8	5*	13*	10	7	8
Additional cleaning / disinfecting slaughterline[1]	7	11*	0*	8	11*	3*
More distance between carcasses	3	4	3	3	6	2
Other	8	9	6	5	3	14
Total	100	100	100	100	100	100

[1] such as automatic rinsing of the saw blade after each carcass
*: $p<0.05$

Three statements dealt with the slaughterline (Table 8). There was only a difference in opinions between respondents from the Netherlands and Denmark concerning the third statement that ‘An uncontaminated carcass reduces the contamination risk to the following carcass’. Of the Dutch respondents, 57% agreed and 89% of the Danish respondents agreed. With respect to food safety it is important to know the effect of the introduction of infected pigs and contaminated carcasses.

Table 8 Percentage of respondents who agreed with the statements with respect to the slaughterline, when the ‘do not know’ answers are left out

Statements	% agreed
All pigs can end up as a bacteriological-free carcass at the slaughterline.	77
More contaminated pigs slaughtered in succession result in higher contamination risk to free pigs.	94
An uncontaminated carcass reduces the contamination risk to the following carcass.	67

5.5 Management interventions in chain from breeding through consumer

To improve food safety of pork with respect to *Salmonella* most effectively, it is necessary to know what interventions in the entire chain have to be taken. We asked for the five most effective interventions in the entire chain, regardless of the costs, to reduce the prevalence of *Salmonella*-positive carcasses.

If seven interventions were to be implemented, the combination of the following interventions was expected to be the most effective: use of acidified feed in primary stages, logistic slaughter, decontamination of carcasses, extensive hygiene at the slaughterhouse and the primary stages, purchase of certified *Salmonella*-free piglets in the finishing stage and informing consumers on storing and preparation of meat. For the optimal performance of the entire pork supply chain with respect to human salmonellosis caused by pork, these interventions should be implemented.

The pork supply chain can be divided into four parts: consumption (consumer stage), process and retail (boning through retail), harvest (transporting finishing pigs through slaughter) and pre-harvest (breeding through finishing stage). Respondents from Animal production assigned the largest part of the contamination of the end product to the harvest part and respondents from Retail & Policy to the pre-harvest part of the pork supply chain. Chain participants seem to put most stress on participants in other stages than their own.

6 Results: Course of infection and contamination

6.1 Course of infection in finishing pigs

In the survey, estimations for the duration of five states of the epidemiological model (Figure 2) were asked. Between 12 and 22 respondents estimated the duration of the periods. The average and standard deviations are shown in Figure 3. Three respondents indicated that the most likely and the maximum duration of several states could last to over a year. These estimations had a large influence on the averages. Since a finishing pig lives only six months, the estimations were maximised at 180 days.

The number of respondents varied among the questions. The number of respondents from Animal production was 3 to 4 and from Retail & Policy the number was 1 to 2. Therefore, a proper comparison among groups with respect to background was not possible. Estimations on the duration of these six states appeared to be difficult.

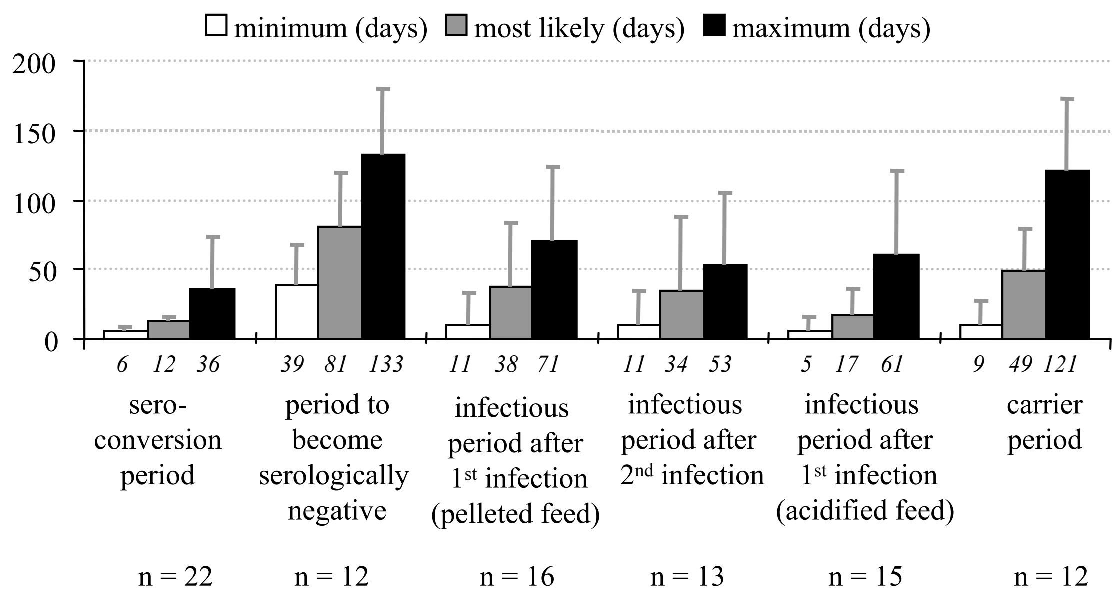

Figure 3 Averages and standard deviations of the estimation for the minimum, most likely and maximum duration of six states in the course of infection of *Salmonella* in finishing pigs

The infection rates of *Salmonella* in pigs in a group with susceptible pigs that were serologically negative or positive are shown in Figure 4. Twenty respondents answered these questions, seven of whom noted no difference in infection rate between the serologically negative and positive pigs. The rest of the respondents valued the infection rate lower in the group with serologically positive pigs.

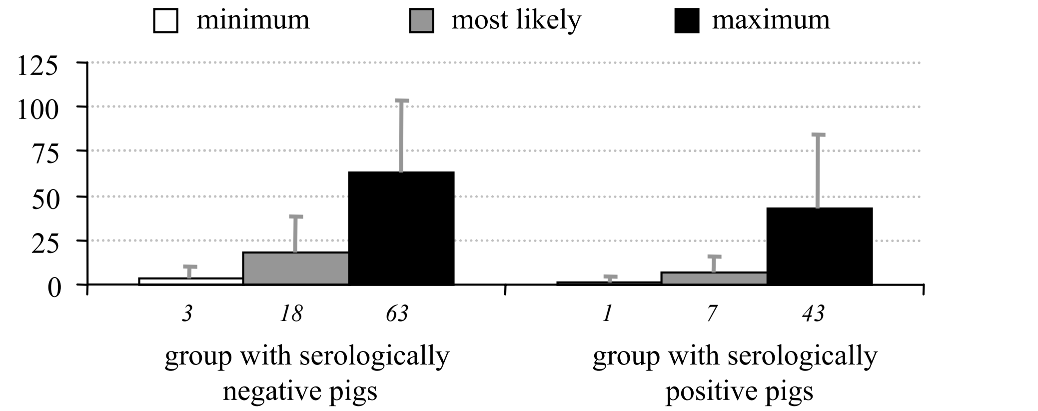

Figure 4 Number of pigs in a group of 100 pigs that can become infected by one infectious pig within a day

One statement was about the difference in sensitivity between serologically negative and positive pigs. In the estimation of the infection rate, the consistency could be tested. About 30% of the respondents who answered both questions were not consistent. For instance, they did not agree with the statement that serologically positive pigs were less sensitive than a serologically negative pig, but in the estimations they estimated that the infection rate in a group with serologically positive pigs was lower than in a group of serologically negative pigs. This inconsistency could mainly be observed in respondents with the backgrounds Animal production and Retail & Policy.

The Dutch respondents estimated the infection rates slightly higher than the Danish respondents did. The average of the estimation of the most likely probability of introduction of *Salmonella* on finishing farms was 0.2% and the minimum percentage was 0.0%. The maximum percentage varied among the groups. The overall average for the maximum percentage was 10%. The respondents from Animal production estimated the risk at 22%, which was much higher than Research with 7% and Retail & Policy with 1%.

6.2 *Contamination at the slaughterline*

All respondents agreed that the number of free carcasses that can be contaminated increases as the number of contaminated carcasses increases (Figure 5). The estimation of the maximum number of carcasses varied between 1 and 1000 carcasses.

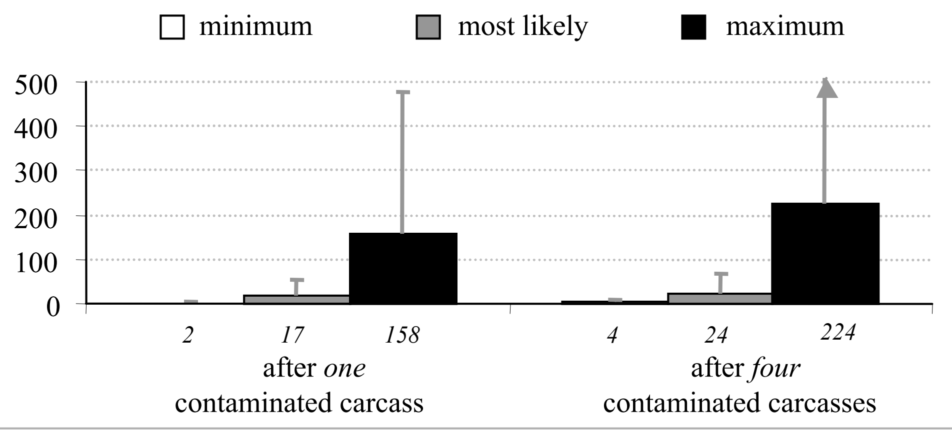

Figure 5 Number of *Salmonella*-free carcasses that can become (in)directly contaminated by the preceding contaminated carcass(es), (n = 14 respondents)

Results show that the knowledge about the course of contamination is limited. Nevertheless, knowledge about the course of contamination is essential to improve the performance of slaughterhouses and consequently the performance of the supply chain. Hence, to fulfil the demand of increased food safety and to be able to select the most cost-effective interventions, it is essential to get more insight in this kind of knowledge.

7 Discussion and Conclusion

Although the response rate of over 50% was good, many respondents did not answer all questions. In section 4 some reasons were given. For determination and ranking of interventions a survey among experts is a useful tool to use. For the comparison of different categories of respondents, more respondents per category are needed than were available in this research. Including experts from more countries could solve the shortage of experts available in a country. The disadvantage of this solution is that the structure of the pork supply chain differs largely between countries. In new research the deliberation to include more countries depends on the number of experts available in a country per category and on the specific supply chain under investigation.

The aims of the survey with experts were to determine and rank management interventions to reduce the introduction and spread of *Salmonella* in the pork supply chain and to compare the opinions from experts from different countries and with a different background.

The ranking of the management interventions in the primary stages shows that most emphasis is on the reduction or prevention of spread of *Salmonella* within the farm. At transport, lairage and slaughter the emphasis was on preventing cross-contamination. Two stages in the chain (finishing and slaughtering) are expected to be able to improve the food safety of pork with respect to *Salmonella* most effectively. Some management interventions such as logistic slaughter have a large impact on the organisation of the entire pork supply chain. In these cases co-operation between supplier and buyer is essential and there is a possibility of joint investments. Before participants in a chain can introduce such co-operation, insight is needed in the exact interventions per stage. This insight is obtained in this paper.

As could be expected, the variation among respondents concerning the estimation of parameters about the course of infection and contamination is wide. The knowledge about these parameters is still limited and further research should focus on the course of infection in practice.

The differences between respondents from the Netherlands and Denmark were small. Since the numbers of Danish respondents from Animal production and Retail & Policy were limited (n=2 and n=4), the Danish results were mainly determined by respondents from Research. The differences in the opinions of respondents from different backgrounds (Animal production, Retail & Policy and Research) can mainly be seen in the relative importance of certain management interventions. Respondents from Research seem to attach most importance to interventions that are presented in recent literature, such as feeding non-heated grains, the dilemma of feed withdrawal before transportation and shortening waiting times at the lairage. The other respondents attached more importance to more general interventions, such as hygiene.

With respect to co-operation and fine tuning processes in the pork supply chain, evaluations as presented in this paper are important. In this case it was focussed on interventions of one specific aspect of food safety. Also for other issues in which multiple stages of a supply chain are involved, a solid basic knowledge about the conditions and consequences for each stage are necessary. The perception of participant of different stages can differ, which is important to know before initiating co-operation between stages.

Acknowledgements

The authors would like to thank Danilo M.A. Lo Fo Wong from the Danish Veterinary Laboratory for his contribution in selecting Danish experts. The authors thank all respondents for completing the survey. The research was co-financed by Agro Chain Competence in the Netherlands, Nutreco and Nedap Agri.

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Appendix

Statements: All statements are presented to the Dutch respondents, statements marked with an asterisk (*) are presented to the Danish respondents.

1. *Salmonella* typhimurium is the most common *Salmonella* type in pigs.
2. The characteristics of *Salmonella* typhimurium can be used for studies about *Salmonella* in pigs.
3. A *Salmonella* infection is sub-clinical in pigs.
4. * *Salmonella* infections do not influence the production results of finishing pigs.
5. * After the infectious period a pig remains (temporarily) a carrier, e.g. in intestines or lymph nodes
6. * After the carrier period a pig remains (temporarily) serologically positive.
7. * The sensitivity to *Salmonella* does not depend on race, weight or sex.
8. * After a pig having gone through an infection, it is less sensitive to a new *Salmonella* infection.
9. * The course of a *Salmonella* infection can be represented as in Figure 2.
10. Only in case that a pig starts shedding, it moves from state S1 to I1, otherwise it remains in state S1.
11. Not all pigs go through an infection equally, in other words some pigs shed longer or remain longer in the carrier state.
12. A pig is serologically positive in case the antibodies are detectable by the standard ELISA test.
13. * The infectivity of infectious pigs is about equal in states I1, I2 and I3.
14. In each stage three infection routes can be distinguished: a) directly by an infective pig in a group within a compartment, b) indirectly by an infective pig at the farm or firm and c) by external causes such as feed, visitors, materials et cetera.
15. The infection rate within a compartment depends on the number of infective pig in that compartment.
16. The infection rate within a farm or firm depends on the number of infective pigs in that farm or firm.
17. Pigs from a *Salmonella* free farm are at risk during transport to catch an infection by *Salmonella* bacteria that are present in the truck from former transported pigs.
18. * <u>All</u> carrier animals become infectious during transportation (i.e. start shedding).
19. During transportation and in the lairage the number of infectious animals can remain the same or increase, it can not decrease.
20. During transportation and in the lairage the serologically status of a pig remains the same.
21. In the lairage a pig can become infected by bacteria present in the lairage from former pigs or by the so-called ‘house-flora’ in the lairage.
22. * The more infectious pigs are unloaded in the lairage, the higher the risk for susceptible pigs to become infected.
23. * All pigs can end up as a bacteriological-free carcass at the slaughterline.
24. During the slaughterprocess a pig/carcass can become contaminated by a) the so-called ‘house-flora’, b) pigs slaughtered before that day and c) external factors such as employers, materials.
25. * More contaminated pigs slaughtered in succession result in higher contamination risk to free pigs
26. * An uncontaminated carcass reduces the contamination risk to the following carcass.

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Chapter 3

A state-transition simulation model for the spread of Salmonella in the pork supply chain

Abstract

A major food safety issue in pork is Salmonella contamination. A stochastic state-transition simulation model was described to simulate the spread of Salmonella from multiplying through slaughter, with special emphasis for critical control points to prevent or reduce Salmonella contamination. Design of Experiments and metamodelling were used for a sensitivity analysis. The finishing stage and the slaughterhouse appeared to be the most important stages in the supply chain to reduce the prevalence of Salmonella contaminated carcasses.

1 Introduction

In agribusiness, there is an increasing interest for human food safety. The major issues are food borne diseases, like salmonellosis, listeriosis and *Escherichia coli* infections. In developed countries, salmonellosis has the highest incidence of food borne diseases and therefore is accountable for considerable societal costs (Anonymous, 2001). The disease is caused by bacteria from the genus *Salmonella* and can result in severe gastro-enteritis, enteric fevers and septicaemia. It is estimated that 90% of the human salmonellosis is food borne (Anonymous, 2001) and about 15% of the food borne salmonellosis originate from pork (Berends et al., 1998). To reduce the incidence and the societal costs, more insight is needed in the epidemiological transmission routes and the possibilities to reduce or prevent *Salmonella* in food products. *Salmonella* bacteria can enter the supply chain in many stages of the process, e.g. in the primary stages by feed, people or rodents, during transportation by infected trucks or at the slaughterhouse by (cross)contamination of infected animals. Hence, for an effective control, the entire supply chain must be involved (e.g. Berends et al., 1998; Lammerding and Fazil, 2000). Since at the moment there are no regulatory or economic incentives to reduce the prevalence of *Salmonella* for the separate stages in the Netherlands, it is not likely that the chain partners are optimising the production process to improve the food safety with respect to *Salmonella* contamination. Because of the ubiquity of the bacteria, it seems unlikely that zero prevalence in the entire pork supply chain can be reached and maintained. In any case, before putting all kinds of control measures and rules into practice, in particular more insight is needed in the (cost)effectiveness of certain control measures. However, extensive real life experimentation is impossible, because it is costly and disruptive. Computer simulation is an attractive alternative to the implementation of explorative control strategies (Dijkhuizen and Morris, 1997). An epidemiological model for the introduction and spread of *Salmonella* in multiple stages of the pork chain is still lacking. Since *Salmonella* in the pork chain is an emerging issue, a model was designed to provide a tool to get more insight in the dynamics of *Salmonella* in the pork chain.

A detailed stochastic state transition model is designed to simulate the introduction and spread of *Salmonella* in the pork supply chain. In this paper, we describe the model in detail, illustrate its behaviour, and perform a sensitivity analysis. The ultimate purpose of the model is to obtain insight in the epidemiological consequences of control measures, of information flows within and between stages and of the impact of having multiple relations between stages, the so-called contact structure. So the most effective combination of control measures including their costs, the information flows and contact structure can be obtained by executing scenarios with realistic combinations of control measures to improve the food safety of pork with respect to *Salmonella*.

In section 2 the pork supply chain and characteristics of *Salmonella* infections in pigs are described. In section 3 the model description is given in detail, in section 4 the sensitivity analysis is described and the conclusions and discussion are presented in section 5.

2 *Salmonella* in the Pork Supply Chain

In Europe *Salmonella* enteritidis and *Salmonella* typhimurium account for about 75% of *Salmonella* isolated from humans (Fisher, 1997). The latter is also the most prevalent serotype of *Salmonella* in pigs. In general, this bacterium type does not cause clinical illness in pigs. An animal that is infected with *Salmonella* can start shedding bacteria and therefore become infectious within 4 hours (Fedorka-Cray et al., 1994). The seroconversion period (to reach detectable antibody levels after infection) is about two weeks. Upon recovery, an animal can remain in a carrier state (bacteria in intestines or lymph nodes, but no shedding), and may become serological negative again. At the slaughter stage bacteria from the intestines or lymph nodes can contaminate the carcass and thereby contaminate pork products (Lettelier et al., 1999). The prevalence (i.e. percentage of infected pigs in a population) can be measured by serological or bacteriological tests. Based on serology, at population level the mean prevalence in finishing pigs is 26% in the Netherlands (Van der Wolf, 2000). The mean bacteriological prevalence of tissues or carcasses after slaughter is 11% in the Netherlands (Swanenburg, 2001). The pork supply chain consists of several stages. Figure 1 shows the different stages in the chain: breeding, multiplying, finishing, transportation, slaughtering (lairage and slaughter), processing, retail and consumer. All stages have relations with partners that are linked to the main food supply chain, like feed companies and service suppliers.

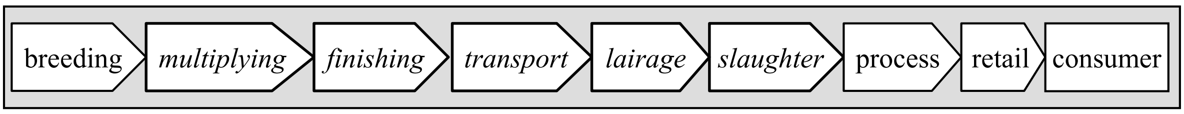


Figure 1 Schematic structure of the pork supply chain. The stages written in *Italic* script are included in the simulation model.

The primary stages (breeding through finishing) are for the larger part specialised family farms. The breeding stage produces sows for the multiplying stage. On the multiplying farm finishing pigs are produced, and at approximately 25 kilograms live weight these are sold to the finishing stage. Multiplying and finishing may be on the same farm or the pigs are transported by trucks of the multiplying farm or by specialised transport companies. In the finishing stage the pigs are fattened to a live weight of approximately 110 kilograms. The regular housing system is a barn with separated compartments where each compartment consists of eight to twelve pens with ten animals each. In general, there are approximately 100 animals in a single compartment. The animals in pens next to each other can have contact by nose and manure. An all-in-all-out routine by compartment is applied by and large. Specialised private transport companies arrange the transportation of the pigs from the finishing farm to the slaughterhouse. At the slaughterhouse, pigs stay in the lairage for a few hours, before being slaughtered, processed, and transported to the retailer. The model includes the stages multiplying up till slaughter. The multiplying stage and the first transport stage are combined in the model and will be presented further as the multiplying stage. The slaughter stage includes the slaughtering of the pigs and the chilling of the carcasses.

Table 1 shows specific control measures and routines that can be implemented per stage to prevent or reduce the introduction and spread of *Salmonella* (Blaha, 2000; Stege et al., 2001; Van der Wolf, 2000). Farms or firms in a stage that take these control measures are considered to have a low-risk profile. A farm or firm with a high-risk profile does not take these control measures and may follow routines that have a higher risk for introduction or spread of *Salmonella*.

Table 1 Major control measures and routines per stage that determine the risk profile

Stage	Low risk	High risk
Multiplying	•certified Salmonella (S.) free feed •fermented feed for piglets •functional hygiene lock •cleaning and disinfecting / round	•pelleted feed (unknown S. status) •free entrance for visitors •no structural rodent control
Finishing	•purchase of certified S. free piglets •fermented feed / non-heated barley •functional hygiene lock •no contacts between compartments	•pelleted feed (unknown S. status) •free entrance for visitors •no structural rodent control •no all-in-all-out
Transport	•cleaning and disinfecting each ride •smooth, good cleanable materials •quiet driving and short distances	•no fasting of pigs before transport •pigs from several compartments in finishing farm mixed in one truck
Lairage	•good hygiene •reduced sojourn (< than 2 hours)	•mixing of pigs from different origin •open fences between compartments
Slaughtering	•cleaning equipment during the day •careful evisceration	•no direct packing of rectum •less time for evisceration

3 Model description

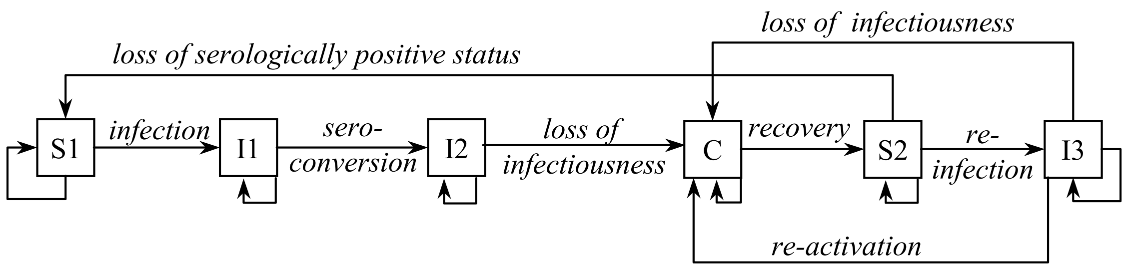
The basic unit of the model is a group of 100 animals. So, each group of 100 animals moves as one unit through the entire model. A group is accommodated in one compartment in the finishing stage, then transported in one truck to the slaughterhouse, and kept together in the lairage. The pigs from one group are slaughtered in random order and remain in this order during the slaughter and chilling process. Among individual farms and firms in the supply chain there is a contact structure, since one stage sells the animals to the next stage. This contact structure is a key issue for the introduction and spread of *Salmonella* in the supply chain. In the model different contact structures can be simulated. For instance only one-to-one relations (each farm or firm purchases to and sells from only one other farm or firm) and more complex contact structures where farms or firms have multiple relations with farms and firms in other stages. In a more complex structure, one farm with a high prevalence of *Salmonella* can contaminate several farms/firms in the following stage.

3.1 Stochastic state transition modelling

The course of *Salmonella* infections in pigs and the spread of the bacteria was modelled by using a discrete time stochastic state-transition approach (Alban et al., 2002). The core of the model consists of two components: states which are combined in state vector $\mathbf{x}(t)$ and transition probabilities $p_{i,j}(t)$ which are collected in a time-dependent matrix of transition probabilities $\mathbf{P}(t)$ (Winston, 1994; Hillier and Lieberman, 1995). The transition probability $p_{i,j}(t)$ gives the probability for an animal in state i to go to state j from one timestep to the next. The time step used in the model equals one day. As from here $p_{i,j}(t)$ will simply be written as $p_{i,j}$. State vector $\mathbf{x}(t)$ contains six different states (described in section 3.2) and the 100 animals of one group are distributed over these states. The number of animals within a group and therefore within the vector $\mathbf{x}(t)$ remains 100. Every time step the distribution of animals within one group over the states is recalculated by the model to a new distribution in state vector $\mathbf{x}(t+1)$. In our implementation the probabilities $p_{i,j}$ in the matrix $\mathbf{P}(t)$ are used in a Monte Carlo simulation for each animal in vector $\mathbf{x}(t)$. In short, the basic unit of the model is a group of 100 animals in vector $\mathbf{x}(t)$ and the transitions within this vector take place on individual animal basis. Notice that the values of the probabilities may depend on the decisions or control measures that are taken to prevent or reduce the introduction or spread of the bacteria (see Appendix). In the model the set of control measures is translated to risk profiles, whereas farms and firms that implemented all control measures as stated in Table 1 are considered to have a low risk profile. The model is designed in Delphi 5 (Borland, 1999).

3.2 States and transition probabilities

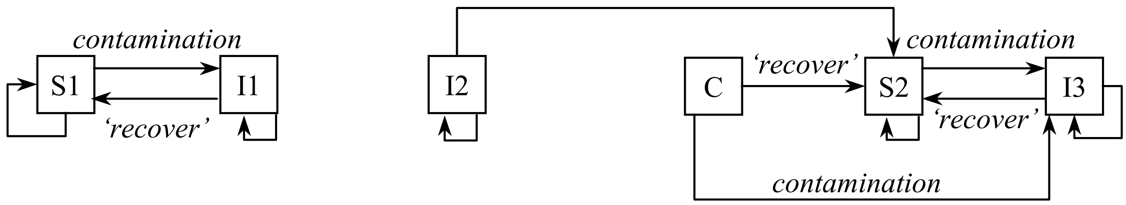
In live animals, the general course of an infection is determined by commonly accepted epidemiological rules (Noordhuizen et al., 1997). This section describes the specific course of a *Salmonella* infection for an individual pig within a group. The states and possible transitions for a live pig are outlined in Figure 2A. This Figure is based on the stochastic SIR (stands for: Susceptible Infectious Recovered) model that is designed to model the spread of a pathogen in a population (e.g. De Jong, 1995; Velthuis et al., 2002). In the SIR model, an animal has to be situated in one of the three following states: susceptible, infectious and recovered. To model the spread of *Salmonella* in pigs, six states are distinguished: two susceptible states (S1 and S2), three infectious states (I1, I2 and I3) and one carrier state (C). In each state there is a probability that an animal remains in the same state from one time period to the next time period. Figure 2A starts with a *Salmonella* free pig (S1) that can become infected and infectious (I1) and after the seroconversion period it will be in I2. When the animal stops shedding it moves to the carrier state (C) and can become susceptible again (S2). An animal in state S2 can get infected and infectious again (I3) or become serological negative (S1). It is assumed that there is no infection induced mortality (e.g. Fedorka Cray et al., 1994).



S1	=	susceptible 1	*Salmonella* free animals,	negative serology
I1	=	infectious 1	infected and infectious animals,	negative serology
I2	=	infectious 2	infected and infectious animals,	positive serology
C	=	carrier	carrier animals, not shedding,	positive serology
S2	=	susceptible 2	susceptible again,	positive serology
I3	=	infectious 3	> 1st infection	positive serology

Figure 2A States and transitions for live animals

After the animal is killed in the slaughterhouse several transitions, like seroconversion, are impossible. Hence, the serology of the animal does not change anymore during or after slaughter, though in the blood or meat drip of the carcass the serology status may still be detectable. The possible transitions during slaughter are outlined in Figure 2B. The interpretation of some states differs slightly from those in Figure 2A. Instead of an infected animal, the I-status should be interpreted as a contaminated carcass, which may be caused by bacteria from the intestines or lymph nodes during evisceration or by cross-contamination at the slaughterline. An infected pig (I1, I2 or I3) may become a carcass free of *Salmonella* (S1 or S2) if the evisceration is carried out very carefully and no bacteria contaminate the carcass. On the other hand a *Salmonella* free pig (S1 or S2) may become infected because of cross contamination by bacteria of other infected carcasses or by bacteria on the slaughter equipment. The carrier state (C) does not exist after slaughter because a carrier carcass is either a contaminated (I2 or I3) or an uncontaminated carcass (S2).



S1 =	susceptible 1	*Salmonella* free carcass,	negative serology
I1 =	infectious 1	contaminated carcass,	negative serology
I2 =	infectious 2	contaminated carcass,	positive serology
C =	carrier	carrier is not a state of a carcass	
S2 =	susceptible 2	*Salmonella* free carcass,	positive serology
I3 =	infectious 3	contaminated carcass	positive serology

Figure 2B States and transitions for carcasses

The transition probabilities p_{ij} are represented in probability matrix **P**(t). Each time step the probabilities are recalculated by equations as outlined in section 3.2.1 till 3.2.5, which depend on the risk profile of the farm or firm. Management and other control measures with respect to prevention and reduction of *Salmonella* determine the risk profile of a farm or firm (see Table 1). Besides these control measures, monitoring and surveillance may also influence the probabilities in the matrix. An example of the matrix for the finishing stage is in section 3.2.2 (equation 1). In this section the relevant probabilities are worked out per stage.

3.2.1 Multiplying stage

The stages multiplying and transport to the finishing stage are combined in the model. According to e.g. Berends (1998) and Funk et al. (2001), the impact of the multiplying stage is limited. Therefore the model starts with the last phase of the multiplying, that is the moment the pigs are transported to the finishing stage with a live weight of 25 kg. The model starts with all individuals in state S1 and then the probability matrix $\mathbf{P}_1$ determines the distribution over the states for each group that enters the first stage. In the multiplying the $p_{i,j}$ in matrix $\mathbf{P}_1$ are $p_{S1,I2}$ and $p_{S1,S1}$, whereas $p_{S1,S1}$ equals $1 - p_{S1,I2}$ (more detailed explanation is in the next sub-section about the finishing stage). Animals that become infected during the multiplying stage went in reality through the infection-cycle as mentioned in Figure 2A from S1 via I1 to I2. So, depending on the risk profile of the multiplying farm, animals within a group that leave the multiplying stage are distributed over the two states S1 (naïve susceptible) and I2 (infectious and serological positive).

3.2.2 Finishing stage

The average sojourn time for a group in the finishing stage is 113 days. The sojourn time (τ) may vary due to the performance of the farm. It is assumed animals in a group mix randomly, so all animals within a group have an equal probability to have contact with each other. As mentioned before, in practice a group is divided in 10 pens with 10 animals each. However, the fences between adjacent pens usually are open, and animals of adjacent pens can infect animals in other pens rapidly. The transition matrix $\mathbf{P}(t)$ for the finishing stage is given in equation 1. Many transitions are biologically impossible and are set to zero in the transition matrix.

Equation 1 shows the transition matrix $\mathbf{P}(t)$ for the finishing stage:

$$\mathbf{P}(t) = \begin{pmatrix} 1-p_{S1,I1} & p_{S1,I1} & 0 & 0 & 0 & 0 \\ 0 & 1-p_{I1,I2} & p_{I1,I2} & 0 & 0 & 0 \\ 0 & 0 & 1-p_{I2,C} & p_{I2,C} & 0 & 0 \\ 0 & 0 & 0 & 1-p_{C,I3}-p_{C,S2} & p_{C,S2} & p_{C,I3} \\ p_{S2,S1} & 0 & 0 & 0 & 1-p_{S2,S1}-p_{S2,I3} & p_{S2,I3} \\ 0 & 0 & 0 & p_{I3,C} & 0 & 1-p_{I3,C} \end{pmatrix} \quad (1)$$

The transition from S1 to I1 is the most important one: in the absence of infection of susceptible animals, the pathogen will disappear from the population. The probabilities $p_{S1,I1}$ and $p_{S2,I3}$ are determined by three independent infection routes. First, animals can be infected by infectious group members in the same group (PG). Second, animals can be infected by infectious animals in other groups on the same farm (PF). No difference is made between compartments alongside the concerned compartment and compartments that are not alongside. Third, animals can be infected by external factors like feed or rodents (PE). These probabilities PG, PF and PE depend on the risk profile of the farm as outlined in the previous chapter.

As outlined before, $p_{S1,I1}$ is determined by the probability of infection from within the group (with probability PG), within the farm (probability PF), and from external sources (PE). As a consequence, an animal will escape infection if it is not infected by its group mates (probability 1-PG), by animals on the farm (probability 1-PF), nor by external sources (probability 1-PE). Hence, $p_{S1,I1}$ is given by

$$p_{S1,I1} = 1 - (1-PG)(1-PF)(1-PE) \qquad (2)$$

Below we will define the probabilities PG, PF and PE in more detail. By standard arguments (Miller, 1979) the probability that an individual is infected by the animals in the same group is given by

$$PG = 1 - e^{-(\beta 1*(Igroup/Ngroup))} \qquad (2a)$$

where Igroup is the number of infectious individuals in a group, Ngroup is the total number of individuals in a group (always 100 individuals), and β1 is the infection parameter. Loosely speaking, β1 can be interpreted as the rate at which a single infected individual infects susceptibles in a population of susceptibles.

Likewise, the probability that an individual escapes infection from the other animals (1-PF) can be given by

$$PF = 1 - e^{-(\beta 2*(Ifarm/Nfarm))} \qquad (2b)$$

where Ifarm is the number of infectious individuals in the entire farm, Ngroup is the total number of individuals in the entire farm, and β2 is the infection parameter.

The probability that an individual escapes infection by external sources (1-PE) is given by the product of probability that it escapes infection by visitors or employees (1-PP), that it escapes infection by contaminated feed (1-PV), and that it escapes infection by still other external factors (1-PO). Hence, PE is given by

$$PE = 1-(1-PP)(1-PV)(1-PO) \qquad (2c)$$

The probability $p_{S2,I3}$ that a previously infected but currently susceptible individual is infected is determined in the same manner. The only difference is the introduction of the 'immunisation factor', which regulates the susceptibility of susceptible, but serologically positive pigs. Since there is no evidence that this immunisation factor is different for the separate probabilities in equation (2), the following equation for $p_{S2,I3}$ is defined:

$p_{S2,I3} = \psi\, p_{S1,I1}$, (3)

where ψ is an 'immunisation parameter' ($0 \leq \psi \leq 1$).

Several transmission studies indicate that the infectious period for *Salmonella* infections in pigs is at least approximately exponentially distributed (Kampelmacher et al., 1970; Nielsen et al., 1995). The recovery rate is denoted by α, so that the probability that an infected pig is still infected Δt time units later, is given by $e^{-\alpha\Delta t}$, and the mean infectious period is $1/\alpha$. Hence, the probability that an infected individual moves to the carrier state ($p_{I2,C}$) in a time interval of unit length is given by $1\text{-}e^{-\alpha}$ (Carpenter, 1988). Moreover we will also assume that the seroconversion period (Nielsen et al., 1995) and the carrier period are also exponentially distributed, with parameters δ and γ. The susceptibility of so-called naïve animals (S1: not infected with *Salmonella* and therefore bacteriologically and serologically negative) is higher than of animals in state S2. The serological positive status gives some degree of immunisation and for some serogroups of *Salmonella* there may be also a matter of cross immunisation (Mittrücker et al., 2000). The exact values of this (cross)immunisation are not clear yet, so the susceptibility of S2 and C animals is implemented in the model as a fraction (quantified here as ψ, where $0 \leq \psi \leq 1$) of the susceptibility of S1 animals.

As stated before, sojourn times are exponentially distributed, resulting in equations (4) through (8):

$p_{I1,I2} = 1\text{-}e^{-\delta}$ δ= 1/seroconversion period (1/day) (4)

$p_{I2,C} = 1\text{-}e^{-\alpha 1}$ $\alpha 1$= 1/infectious period for first infections (1/day) (5)

$p_{C,S2} = 1\text{-}e^{-\gamma}$ γ = 1/carrier period (1/day) (6)

$p_{I3,C} = 1\text{-}e^{-\alpha 2}$ $\alpha 2$= 1/infectious period for second or third infections (1/day) (7)

$p_{S2,S1} = 1\text{-}e^{-\varphi}$ φ= 1/period to become serological negative (1/day) (8)

3.2.3 Transportation stage

The duration of the transport from the finishing farm to the slaughterhouse varies from one to six hours. Although in the stages transport and lairage the states and transitions for live animals are used, some transitions of Figure 2 are excluded, due to the short duration time in these stages. First, transitions to another serological state are impossible (consequently $p_{I1,I2} = 0$ and $p_{S2,S1} = 0$), and second, infectious animals remain infectious during transportation and lairage ($p_{I2,C} = 0$ and $p_{I3,C} = 0$). Equations 2 and 3 are used to calculate

$p_{S1,I1}$ and $p_{S2,I3}$ for transport as well. Because there is only one group transported in a truck, PF is set to zero during transport. The probability to introduce an infection at the truck by previous transported groups is included in the PE. Since animals are not fed during transport, the probability PP (probability to become infected by contaminated feed) is set to zero. Due to stress and fasting before and during transport, the transition from the carrier state to the infectious state ($p_{C,I3}$), is increased by a constant probability.

3.2.4 Lairage

As with transportation, the sojourn time in the lairage is too short for some of the transitions of Figure 2A to occur. Specifically, $p_{I1,I2} = p_{S2,S1} = 0$, just like all transitions to the carrier state. The matrix **P**(t) for the lairage includes the following probabilities $p_{i,j}$: $p_{S1,I1}$,$p_{S2,I3}$ and $p_{C,I3}$. All infectious animals remain in the same state. The risk profile of the lairage determines the $p_{C,13.}$ The equations for $p_{S1,I1}$ and $p_{S2,I3}$ i.e. (2), (2a) and (2c) are the same as used in the finishing stage, although with different variable values of course. Equation 2b from the finishing stage is different at lairage and rewritten below in equation 9 and 10. In the lairage, groups of pigs from different finishing farms are collected together and may infect each other. If a group is unloaded in a compartment in the lairage that has been occupied by a group with a higher prevalence, the probability of infection by the shedding of bacteria from the previous group increases. Conversely, *Salmonella* free groups can lower the risk of infection for subsequent groups (Swanenburg, 2000). Therefore the equation for PF in the lairage cannot be based on equation 2b of the finishing stage. The prevalence of groups previously present in the lairage will influence the infection pressure in the lairage. The infection pressure is defined as the amount of bacteria in the environment that increases when more infectious individuals have been in the lairage. Therefore, the infection pressure (InfPres(t)) is time dependent and is calculated by simple exponential smoothing as shown in equation 9. This approach is chosen after consultation of experts in the field of spreading *Salmonella* in the lairage. The smoothing factor λ (Winston, 1994) determines the relative impact of the prevalence of the last group entering the lairage. The infection pressure is calculated after each group entering the lairage by

$$\mathrm{InfPres}(t) = (1-\lambda)^{*}\ \mathrm{InfPres}(t-1) + \lambda^{*}\ \mathrm{Prev}(t) \qquad (9)$$

where InfPres(t) is the progressive infection pressure of the lairage at t ($0 \leq \mathrm{InfPres}(t) \leq 1$), and Prev(t) is defined as the prevalence of infectious animals (states I1, I2 and I3) within the group that enters the lairage ($0 \leq \mathrm{Prev}(t) \leq 1$). The variable λ is a smoothing factor that determines the relative impact of Prev(t) ($0 \leq \lambda \leq 1$). The infection pressure (InfPres(t)) determines the probability PF in the lairage.

For simplicity, and since no solid evidence for other assumptions is available, we assume that InfPres(t) and PF(t) are linearly related (see Figure 3). PF(t) has a minimum ($PFmin_{lairage}$) that depends on the risk profile of the lairage and a maximum ($PFmax_{lairage}$) because in practice the PF(t) does not reach the value 1 as not all animals become infected in the lairage. The starting value of the probability to become infected in the lairage by other groups is $PFmin_{lairage}$, so PF(0)= $PFmin_{lairage}$. PF(t) is calculated by equation 10. Each week the PF(t) can be reset to the starting value $PFmin_{lairage}$.

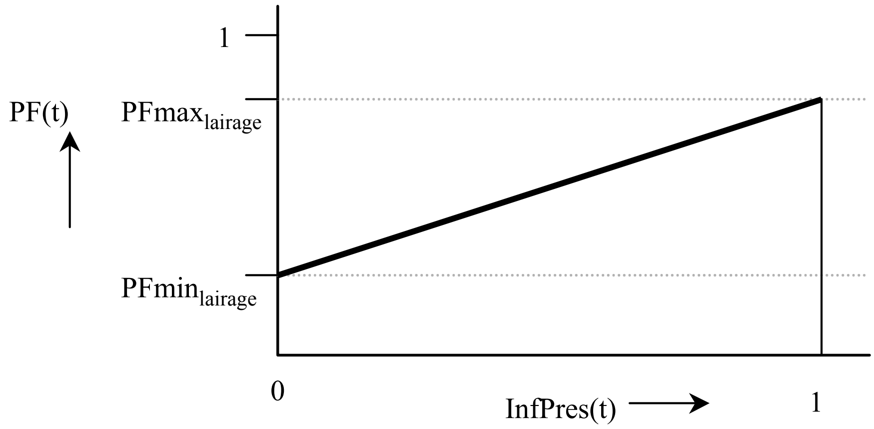


Figure 3 Relationship between the infection pressure in the lairage (InfPres(t)) and the probability of infection by the firm infection route (PF(t))

The equation for PF(t) can be noted as:

$$PF(t) = InfPres(t)\,(PFmax_{lairage} - PFmin_{lairage}) + PFmin_{lairage} \qquad (10)$$

where PF(t) is the probability to become infected (in)directly by bacteria in the firm, like other groups, $PFmin_{lairage}$ is the minimum probability to become infected in the lairage and $PFmax_{lairage}$ is the maximum probability to become infected in the lairage.

3.2.5 Slaughtering stage

As shown in Figure 2B, the pattern of introduction and spread is different in the slaughtering stage for carcasses compared to the live pigs in the preceding stages. In fact, since animals are dead, only (cross)contamination of the carcasses is an issue. Another difference is that the pigs in one group are slaughtered successively. Consequently, no mixing of animals within or among groups can occur. The sequence in which the pigs from one group are slaughtered is randomised. The slaughterprocess can be divided in two processes: the procedure of stabbing till evisceration, and the procedure of evisceration till chilling. Since the knowledge about the spread of *Salmonella* in the slaughtering stage is limited, literature on experiments (e.g. Swanenburg, 2000) and expert knowledge (Van der Gaag and Huirne, 2002) was used to design the epidemiological model for the slaughtering stage.

During the process of stabbing through evisceration, the washing, dehairing, and the removal of the intestines take place. During the process through evisceration an infected pig (states I1, I2, I3 and C) can become a contaminated carcass or become a free carcass if the evisceration is carried out very carefully, and if the equipment is not contaminated. The transition probability depends on the risk profile of the slaughterhouse (equation 11). *Salmonella* free pigs (S1 and S2) deliver free carcasses during the process through evisceration. In practice, pigs that were free before this first process may become infected, but in the model this is included in the second part of the slaughterprocess. The risk profile of the slaughterhouse (in this case the evisceration-process) is determinative for probabilities $p_{I1,S1}$, $p_{I2,S2}$, $p_{I3,S2}$ and $p_{C,S2}$ and the probabilities are given by Qevisc (equation 11). So:

$$p_{I1,S1} = p_{I2,S2} = p_{I3,S2} = p_{C,S2} = Qevisc \qquad (11)$$

where Qevisc is the probability an infectious pig becomes a free carcass in the first slaughterprocess.

The second part of the slaughterprocess, evisceration till chilling, is characterised by two types of transitions: contaminated carcasses can become *Salmonella* free ($p_{I1,S1} = p_{I2,S2} = p_{I3,S2}$, equation 12), and free carcasses can become contaminated ($p_{S1,I1} = p_{S2,I3}$, equation 13). The probability for contaminated carcasses to become pathogen free depends on the risk profile of the slaughterhouse. There is no difference among carcasses from state I1, I2 or I3. So the probability for an infected carcass to end up free is:

$$p_{I1,S1} = p_{I2,S2} = p_{I3,S2} = Qproc \qquad (12)$$

where Qproc is the probability a contaminate carcass ends up as a free carcass in the second slaughterprocess.

The probability that a free carcass is contaminated (PF(t)) depends on the state of the preceding carcasses is specified in equation 12. More contaminated carcasses increase the probability for a *Salmonella* free carcasses to become contaminated. This is included in equation 13a as Qup. Qup is defined as the relative increase of PF(t) after each contaminated carcass. Conversely, more free carcasses will decrease the probability because the equipment will be 'cleaned' by the free carcasses, which is Qdown in equation

13b. Like in the lairage there is a maximum and a minimum probability for this infection route: $PFmax_{slaughter}$, and $PFmin_{slaughter}$. The model recalculates the PF(t) each timestep and this calculation is conditional upon the state of the carcass entering the slaughterline. If the carcass is contaminated (I1, I2 or I3) equation 13a is used and if the carcass is free (S1 or S2) equation 13b is used. Equation 13 is based on expert consultation.

So the probabilities for free carcasses (S) to end up as contaminated carcasses (I) is described by

$$p_{S1,I1} = p_{S2,I3} = PF(t) = PF(t-1) + Qup(PFmax_{slaughter} - PF(t-1)) \quad (13a)$$

$$\text{or } = PF(t-1) - Qdown(PF(t-1) - PFmin_{slaughter}) \quad (13b)$$

where PF(t) is the probability for a *Salmonella* free carcass to become contaminated in the second part of the slaughterprocess at time step t, Qup and Qdown are the increase and decrease of the probability related to the maximum and minimum probability ($0 \leq Qup \leq 1$, and $0 \leq Qdown \leq 1$), PFmax and PFmin are the minimum and maximum probability to become contaminated in second part of the slaughterprocess. Figure 4 shows an example of the fluctuation of PF(t) over time, given a certain sequence of free and contaminated carcasses.

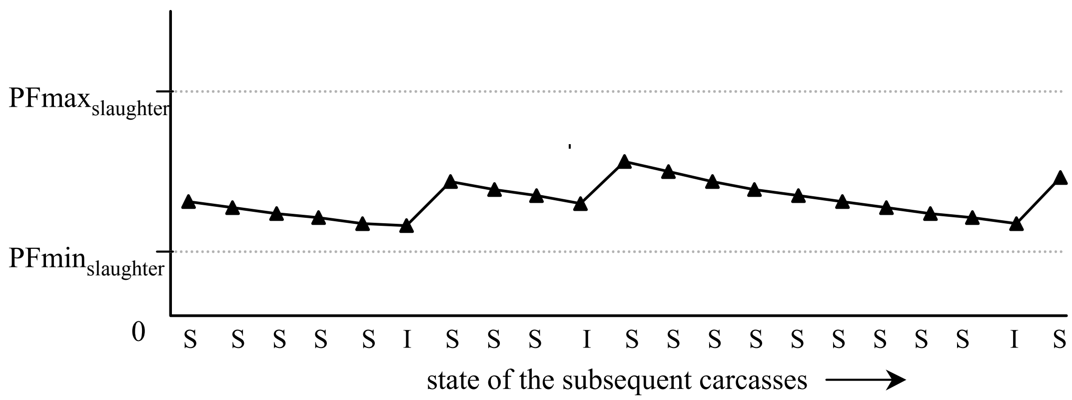


Figure 4 Example of fluctuation of PF(t) over time, where PF(t) is recalculated after each carcass entering the slaughterline; an I carcass increases the PF(t) by Qup (Qup=0,2) and a S carcass decreases the PF(t) by Qdown (Qdown=0,1)

The carcasses that leave the slaughterhouse are distributed over four states: *Salmonella* free and serological negative (S1), *Salmonella* free and serological positive (S2), contaminated and serological negative (I1), and contaminated and serological positive (I2, I3). There is no carrier state (C) anymore. The distribution over these states is the output of the model and will be used to calculate the prevalence of contaminated carcasses.

4 Sensitivity analysis and statistical methods

4.1 Design of experiments (DOE)

The goal of sensitivity analysis is to determine how sensitive the output is to changes of the inputs and if the direction of output changes are consistent with the expected direction (Kleijnen and Sargent, 2000). There are many techniques to do so. According to Kleijnen (1999), a sensitivity analysis is a systematic investigation of the reaction of the output of the simulation model to extreme values of the models' input. So multiple scenarios have to be executed with the model, whereas a scenario is defined as a run with a predefined set of input values. Based on the comparison of techniques by Vonk Noordegraaf et al. (2003), in this paper Design of Experiments (DOE) with metamodelling are executed. Every input variable or parameter has two values: a minimum and a maximum level (Table 2). There is no general prescription how to specify these values (Law and Kelton, 2000). In this case the values were collected using reviewed literature and by conducting a questionnaire among experts (Van der Gaag and Huirne, 2002).

DOE is a specified fractional factorial design that minimises the number of combinations of factor levels (scenarios) that have to be run. The simulation model as described in section 3 had 26 input variables and parameters (from here named 'factors'). Defining the main effect of a factor as the change in model output due to moving the value of that factor from the minimum to the maximum value (Law and Kelton, 2000), a resolution IV design for DOE enables the estimation of main effects not confounded with two-way interactions. The resolution IV design for 26 factors results in 64 scenarios. Each scenario was a run for 1000 timesteps. For more detailed information about DOE, we refer to e.g. Kleijnen (1998; 1999) and to Law and Kelton (2000).

Table 2 Default, minimum, and maximum values of the 26 factors (input variables/parameters)

Stage	Factor	Default Value	Minimum value	Maximum value
Multiplying	$p_{S1,I2}$	0.10	0.001	0.25
Finishing	τ	113	105	122
	ψ	0.75	0.25	1
	δ	1/12	1/7	1/24
	φ	1/60	1/30	1/120
	$\beta1$	0.05	0.005	0.5
	$\beta2$	0.00005	0.000001	0.0005
	$PE_{finishing}$	0.00002	0.000005	0.0005
	$\alpha1$	1/(18-14)	1/2	1/(56-7)
	$\alpha2$	1/14	1/2	1/30
	γ	1/60	1/5	1/120
Transport	ψ	0.75	0.25	1
	$\beta3$	1.5	0.5	2.5
	$PE_{transport}$	0.005	0.00005	0.05
	$p_{C,I3}$	0.35	0.05	0.65
Lairage	ψ	0.75	0.25	1
	$\beta4$	1.5	0.5	2.5
	$PE_{lairage}$	0.005	0.0005	0.002
	λ	0.5	1	0
	$PFmin_{lairage}$	0.001	0	0.05
	$PFmax_{lairage}$	0.1	0.05	0.50
Slaughtering	$PE_{slaughter}$	0.005	0.0005	0.05
	Qevisc	0.75	0.90	0.10
	Qproc	0.75	0.90	0.10
	$PFmin_{slaughter}$	0.001	0.0001	0.05
	$PFmax_{slaughter}$	0.25	0.05	0.50
	Qdown	0.05	0.01	0.50
	Qup	0.10	0.01	0.50

Main source: expert elicitation (Van der Gaag and Huirne, 2002)

4.2 Metamodelling

A metamodel is an approximation of the input-output transformation that is implied by the simulation model (Kleijnen and Sargent, 2000). The metamodel is based on the scenarios defined by DOE. Our metamodel was specified as the following simple first-order polynomial with k variables for each scenario *i*:

$$Yi = \beta_0 + \Sigma^{k}_{h=1} \beta_h x_{i,h} + e_i \quad (14)$$

where Yi denotes a characteristic of the simulation output of scenario i, β_0 is the intercept, β_h the main effect of variable h, $x_{i,h}$ the value of the standardised variable h in scenario i, and e_i the approximation error plus intrinsic noise in scenario i. The β 's are estimated using regression analysis (SPSS, 1999). Notice that these β are not the same as the input parameters β in the model.

The output of the model is the distribution of carcasses within a group over the states as outlined in section 3.2. This distribution over states can be characterised through different quantities, such as its mean and standard deviation. These quantities are estimated based on simulation iterations (Kleijnen and Sargent, 2000), in this sensitivity analysis the number of iterations was set to 1000 timesteps.

The following four output quantities (Yi) were considered (i = 1, .., 4):

Y1: mean number of contaminated carcasses in a group that leave the last stage (i.e. mean number of carcasses that are bacteriological positive that is in state I1, I2, and I3)

Y2: standard deviation (sd) of *Y1*

Y3: mean number of serological positive carcasses in a group that leave the last stage (i.e. mean number of carcasses in state I2, I3, and S2)

Y4: standard deviation (sd) of *Y3*

The mean number of individuals that are bacteriological positive (*Y1*) is important because this is the indicator for the safety of fresh pork products with respect of *Salmonella*. For decision makers it is necessary to know which input variables can have most impact on the standard deviation of the mean (*Y2*) because this is related to uncertainty about the expected level of *Salmonella*. In the field, the prevalence of *Salmonella* on a farm is generally based on the serology of the individuals (*Y3* and *Y4*).

To estimate the metamodel, least squares linear regression using a factor selection procedure called the backward method was used (SPSS, 1999). This means that all factors are entered in the regression model and then sequentially removed. A factor was considered as a significant main effect if $p<0.05$. In DOE with resolution IV design, also two-way interactions can be calculated, although they may be confounded with each other. The factors that were found to be significant main effects were included to test two-way interaction using least squares linear regression with the backward method.

5 Results

Figure 5 shows the cumulative distribution functions for the number of contaminated carcasses per group that leave the slaughterhouse in four different scenarios, based on 1000 timesteps per scenario. The horizontal axis reflects the prevalence of contaminated carcasses per group of 100 pigs. The vertical axis reflects the cumulative percentage of groups that have a prevalence at or lower than the prevalence showed on the horizontal axis. E.g. in case all factors are set to the average value, from almost 20% of the groups that leave the slaughterhouse, the prevalence is less than 0.2 and for over 85% of the groups the prevalence is below 0.3. The following scenarios are shown: all factors at the minimum value, all factors at the maximum value, all factors at the average value between the minimum and maximum, and all factors at the default value (Table 2). All factors at the minimum value result in a very low prevalence and all factors at the maximum value result in a very high prevalence of contaminated carcasses. In practice, these extremes are not likely to occur. Using the default values is a better representation of reality. In further research other combinations of values will be tested. The gradient of the curve is an indication for the variation within one scenario.

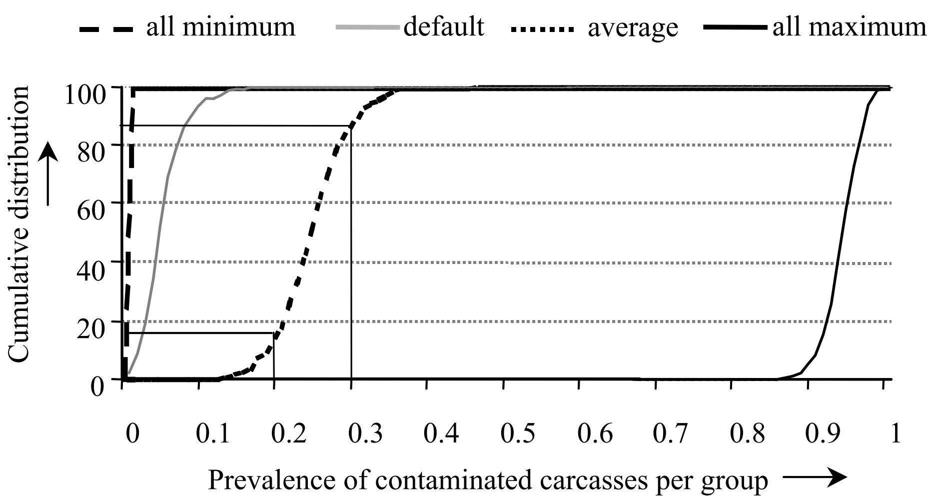


Figure 5 Distribution Function for the number of contaminated carcasses per group that leave the slaughterhouse in four different scenarios (1000 timesteps)

The significant main effects and two-way interactions for each of the four output quantities are shown in Table 3. A positive main effect indicates that changing the factor from its minimum to its maximum value results in an increase in the output value. For instance, increase of the factor $p_{S1,I2}$ in the multiplying stage from 0.1% to 25% (see Table 2,) will increase the intercept of the mean number of serological positive carcasses (*Y3*) with 19.9. In *Y2* the factors Qevisc and Qproc were significant main effects, but adding the two-way interaction to the regression model, only the interaction remained significant. The same is applicable for other main effects, when interaction is introduced. Testing the interactions of the factors for output *Y1* results in three significant interactions at the slaughterhouse.

Table 3 Significant main effects (β_h) and two-way interactions for each output quantity *Y1* through *Y4* ($p<0.05$)

Main factor/ Interaction	Stage	*Y1* (mean I)	*Y2* (sd *Y1*)	*Y3* (mean serol.pos.)	*Y4* (sd *Y3*)
R^2_{adj}		0.88	0.37	0.82	0.19
Intercept		-14.8	2.8	-6.3	4.1
$p_{S1,I2}$	Multiply			19.9	-6.1
β1	Finishing	12.9		44.1	14.5
$\beta1{*}PE_{finishing}$	Finishing			26.4	
Qevisc	Slaughter	-8.2			
Qproc	Slaughter	-7.7			
Qevisc*Qproc	Slaughter	35.1	5.3		
Qdown	Slaughter	-8.2			
Qdown*Qevisc	Slaughter	19.1			
Qdown*Qproc	Slaughter	19.1			

6 Discussion and conclusions

6.1 Main assumptions in the model

To reduce the complexity of the problem of *Salmonella* in the pork supply chain a number of simplifying assumptions had to be made. The main weakness of the model is that some epidemiological processes are not known yet and the assumptions or simplifications made for the calculations of the transition probabilities in the lairage and the slaughterhouse have an unknown influence on the output. Nevertheless, no alternatives were available, but this weakness should be kept in mind interpreting the results. Three other major assumptions in the current model are: 1) a group of animals remains together from multiplying through slaughter; 2) the sojourn times in the states S2, I1, I2, I3 and C are exponentially distributed and 3) the probability of (cross)contamination in the slaughterhouse can be described using the number of infectious animals entering the slaughterhouse. Designing the model these assumptions seemed to be acceptable for us.

The first assumption is not according to current practice in the Netherlands. Finishing farms deliver pigs from one group (i.e. compartment) in two or three phases to the slaughterhouse. Animals from different groups are then mingled. Mingling can be seen as an increase of the probability that infectious animals from one group infect animals from other groups and this is included in the model. However, law in the Netherlands forbids mingling. The second assumption about the exponential distribution of the duration of I2 and I3 is based on several infection experiments (Kampelmacher et al., 1970; Nielsen et al., 1995). Since there is no evidence that the distribution of the sojourn times in state S2 and C are distributed differently, these sojourn times are also assumed to be exponential. The third assumption is based on expert research and personal communications.

6.2 Values of input variables and parameters (factors)

Since real data about transmission within and among groups and longitudinal studies on the prevalence of *Salmonella* in the entire supply chain are limited, most values for the factors are estimations from literature and experts. Using simulation models on an epidemiological base, like the one presented, the effect of the values of the factors on the output can be tested. The model has the flexibility to add new insights as knowledge of the introduction and spread of *Salmonella* in the pork supply chain improves. Simulation models can be valuable in improving understanding of the dynamics and of the impact of various variables and stages. Modelling may also expose deficiencies in the available knowledge of the system being studied allowing the productive direction of future experimental work (Hurd and Kaneene, 1993). In the presented model the direction of output changes after changing the input variables is consistent with the expected direction. The values of some input parameters can be questioned. Especially the duration of the infectious and carrier states in live animals, the infection rates and the exact course of (cross)contamination at the slaughterline could not be based on results from practical research. In most transmission experiments high doses of bacteria are used as a challenge and the results may be not corresponding with the real transmission at farms. To test the necessity of improving knowledge about the values of input parameters the sensitivity analysis showed that these variables may be important for the final existence of *Salmonella* on carcasses.

6.3 Sensitivity analysis and results

Design of Experiments (DOE) and metamodelling with regression analysis gives an indication which factors are most important and which factors deserve most attention in further research. This approach is preferred over the more common changing one factor at the time, since DOE may not only be used for sensitivity analysis, but also for validation (Kleijnen, 1998).

The metamodels for *Y1* and *Y3* had a high R^2_{adj} (0.88 and 0.82), which indicate that the metamodel is a fair predictor for the entire simulation model. The R^2_{adj} for *Y2* and *Y4* were low (0.37 and 0.19) and therefore these results must be handled with more care. The most important output quantity with respect to food safety is *Y1*, the mean number of contaminated carcasses that leave the slaughterhouse. The significant main factor for *Y1* from the finishing stage is $\beta 1$: the rate of infection within a group. This rate may be decreased by feeding strategies and by reducing the possibilities that animals have contact with manure. The slaughtering stage seemed to have even a higher impact on the mean number of contaminated carcasses. And several interactions were found to be significant. Good hygiene in the slaughterhouse, such as rectum removal in bags, careful evisceration and disinfecting of the equipment, reduces the risk of (cross)contamination. The serological status of the carcasses (*Y3*) depends on two main factors and one interaction. A higher starting prevalence ($p_{S1,I2}$) in the multiplying stage and a higher $\beta 1$ results in more infected and therefore serological positive animals. The $PE_{finishing}$ had an understandable interaction effect with $\beta 1$; if the probability that an animal in a group becomes infected increases, the infection rate within the group ($\beta 1$) becomes more important.

6.4 Practical implications and further research

In this paper the purpose was to describe the model and its basic behaviour. In further studies using the model, the effect of different risk profiles on the final prevalence of contaminated carcasses will be simulated. Also the value of information between stages will be tested, for instance in the case of logistic slaughter. This means that the *Salmonella* free groups are slaughtered first to prevent (cross)contamination. The internal spread in the finishing stage and the processes in the slaughter stage are important for the food safety of pork with respect to *Salmonella*. We should focus on these stages in our further research. Furthermore, the model is general in nature and may also be applied for other zoonoses in the pork supply chain.

Acknowledgements

This study was in part financed by Agro Chain Competence, Rosmalen, The Netherlands. We thank Antonie Vonk Noordegraaf for useful help and comments with respect to the DOE analysis.

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Appendix Input variables in the model and dependency on risk profiles

Stage Variable	Depend on risk	
Multiplying		
$p_{S1,I2}$	Yes	Probability a pig leaves the multiplying farm as an infected pig.
Finishing		
τ	No	The sojourn time for groups at the finishing farm.
ψ	No	Immunisation factor (difference in susceptibility between serological negative and serological positive animals).
δ	No	Seroconversion period (in days).
φ	No	Period to become serological negative again (in days).
$\beta1$	Yes	Infection rate within a group.
$\beta2$	Yes	Infection rate within a farm.
PE	Yes	Probability to become infected by feed (PP), visitors (PV) or other external causes (PO) within a time step.
$\alpha1$	Yes	Infectious period after the first infection (in days).
$\alpha2$	Yes	Infectious period after the second or third infection (in days).
γ	Yes	Duration of the carrier period (in days).
Transport		
ψ	No	Immunisation factor (difference in susceptibility between serological negative and serological positive animals).
$\beta3$	Yes	Infection rate within a group.
PE	Yes	Probability to become infected by visitors (PV) or other external causes (PO) within a time step.
$p_{C,I3}$	Yes	Probability that an animal in the carrier state will re-activate.
Lairage		
ψ	No	Immunisation factor (difference in susceptibility between serological negative and serological positive animals).
$\beta4$	Yes	Infection rate within a group.
PE	Yes	Probability to become infected by visitors (PV) or other external causes (PO) within a time step.
λ	Yes	Smoothing factor (determine the relative importance of the prevalence of newly introduced groups on the PF)
PFmin	Yes	Minimum value of PF (= probability to become infected by the lairage within a time step).
PFmax	Yes	Maximum value of PF.
Slaughtering		
Qevisc	Yes	Probability that a bacteriological positive carcass becomes bacteriological negative by evisceration.
Qproc	Yes	Probability that a bacteriological positive carcass becomes bacteriological negative after entire slaughterprocess
PFmin	Yes	Minimum value of PF (=probability to become contaminated by the slaughterline within a time step).
PFmax	Yes	Maximum value of PF.
Qdown	Yes	Relative percentage the PF will decrease after a non-contaminated carcass passed the slaughterline.
Qup	Yes	Relative percentage the PF will increase after a contaminated carcass passed the slaughterline.

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Chapter 4

Cost-effectiveness of controlling Salmonella in the pork supply chain

Abstract

Pork is one of the sources of food-borne salmonellosis in humans. In this paper, the cost-effectiveness of different control scenarios against Salmonella in the stages finishing, transport, lairage and slaughtering is explored. A stochastic simulation model was used for the epidemiological analysis and a deterministic model for the economic evaluation. Results showed that the cost-effectiveness of interventions in the finishing and slaughtering stages is the highest with respect to the reduction of the prevalence of contaminated carcasses. However, the cost-effectiveness is reduced in case not all farms or firms within a stage intervene to reduce the prevalence of Salmonella.

1 Introduction

Pork is one of the sources of food-borne salmonellosis in humans. In the Netherlands, annual societal costs caused by human salmonellosis are estimated between 32 and 90 million Euro (Van Pelt and Valkenburgh, 2001). About 25% of all human cases are caused by serotypes originating from pigs (Van Pelt and Valkenburgh, 2001). Up until now, in the Dutch pork chain there is neither a control system nor a differentiation in payments with respect to the contamination of the product with *Salmonella*. Hence, there is no direct incentive for producers to reduce the *Salmonella* prevalence. However, indirect incentives such as the increased interest for food safety and the large competition on the (international) market for pork, are of increasing importance, since about two third of the Dutch pork is exported (Anonymous, 2001a). Therefore, it is important to get more insight into the trade-off between prevalence reduction and associated costs.

Because of the ubiquity of the bacteria, it is unlikely that zero prevalence in the entire pork supply chain can be reached and maintained. However, from a technical point of view, many strategies on reduction of the prevalence of *Salmonella* have been studied and many conceivable scenarios for improvement of food safety with respect to *Salmonella* appeared to exist. *Salmonella* occurs generally sub-clinically in pigs. *Salmonella* can enter and spread in the pork supply chain in every stage of the process. For example in the primary stages by feed, people or rodents and during transportation and at the slaughterhouse by (cross-)contamination of the environment or infected animals. Hence, for an effective control resulting in a satisfying reduction in the end product, the entire supply chain must be involved (Berends et al., 1998; Lammerding and Fazil, 2000).

Remarkably, economic evaluations are still scarce. From an economic and decision making point of view, the cost-effectiveness in terms of the ratio between the achieved reduction in prevalence (ΔP) and the change in net costs to obtain this reduction (ΔC) is of great importance as well (Belli et al., 2001). It is essential to get insight in which stages most reduction can be achieved cost-effectively with respect to the *Salmonella* contamination of pork.

The objective of this paper is to explore the cost-effectiveness of different control scenarios against *Salmonella* in the Dutch pork chain to determine the most promising scenarios. Multiple scenarios were analysed, whereas each scenario included the epidemiological and economic consequences of interventions in the pork chain on the separate stages and on the pork chain as a whole.

2 Material and Methods

In Figure 1, an overview of the modelling approach and research design is presented. In the pork supply chain, seven stages can be distinguished: breeding and multiplying, finishing, transportation, lairage, slaughtering, processing and retailing and household. The models include the stages finishing through slaughter since the basic end product of the pork is a chilled carcass. A scenario is defined as one simulation run with the epidemiological model, with a certain combination of stages that implement packages of interventions and the net costs for those packages of interventions from the economic model. The input and the models will be described in the next two sections and the output in the section Research design.

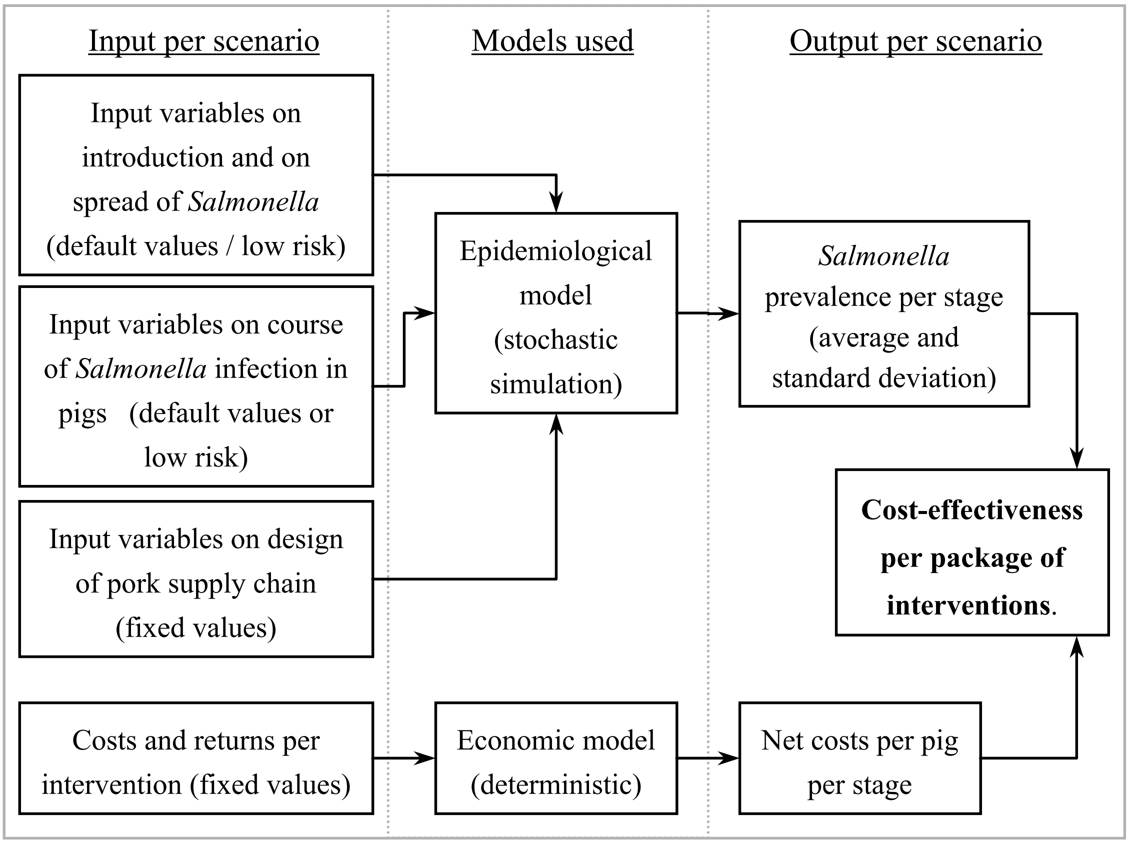

Figure 1 Overview of the research design per scenario

2.1 Epidemiological model

Since it is not possible to test all individual interventions in practice, computer simulation is an attractive way to explore the effect of interventions (Dijkhuizen and Morris, 1997). A stochastic state-transition simulation model was used to simulate the effects of interventions applied in the different stages in the pork supply chain. Interventions are defined as adjusted or new procedures, technical adjustments and control measures. In the model, groups of pigs move through the pork supply chain and may become infected with *Salmonella*. A pig can have three states with respect to *Salmonella*: free, infected (shedding bacteria) or carrier (not shedding, but carrying bacteria in its body). A carcass can have two states with respect to *Salmonella*: free or contaminated.

The epidemiological model has three types of input variables (see Figure 1):
1. input variables directly related to the introduction and to the spread of *Salmonella*, e.g. probability that visitors introduce the bacteria and hygiene interventions to prevent cross-contamination in the slaughterhouse,
2. input variables related to the infection and contamination dynamics, e.g. the duration of the infectious period,
3. input variables related to the design of the pork supply chain, e.g. sojourn time in each stage.

For each input variable, a minimum, default and maximum value is appointed. Van der Gaag et al. (2003) presents a detailed description of the model. The purpose of interventions is to reduce the risk of introduction or spread of *Salmonella* in the pork supply chain. In the simulation model, this is expressed by changing parameters type 1 and 2. E.g. the infection rates in a compartment of farm (parameters type 2) are reduced in case the spread of *Salmonella* between pens or compartments is reduced by interventions. Consequently, the incidence and prevalence of *Salmonella* will be reduced. A list with major interventions in the stages finishing, transport, lairage and slaughtering was composed (presented in Tables 1 to 4). This list was based on literature about *Salmonella* in the pork chain (e.g. Stege, et al., 2001; Davies and Wray, 1997) and on a survey among experts in the Netherlands and Denmark (Van der Gaag and Huirne, 2002).

Table 1 Interventions in the finishing stage and the corresponding net costs

Intervention	€ / pig	Intervention	€ / pig
Adding acid at pelleted feed[1]	1.78	Testing bacteriologically	0.12*
Adding acid to water system[1]	1.73	Testing serologically	0.11
Wet feed[1]	1.48*	Fasting before transport	-0.08*
Hygiene related to spread	0.46*	Logistic supply	n.c.
Hygiene related to introduction	0.77*	Separate delivery room / building	0.24*

[1] Intended intervention is to feed acidified feed; three ways to reach a lower pH in the feed or water are calculated.
* Interventions included in total package of interventions for calculation of cost-effectiveness (interventions that can be implemented in short term and do not overlap considerably with other interventions)

Table 2 Interventions in the transportation stage and the corresponding net costs

Intervention	€ / pig	Intervention	€ / pig
Hygiene truck	0.23*	Quiet loading and driving	0.17*
One compartment of finishing farm/ride	1.92	Changing clothes driver per trip	0.09*
Fasting before transport	0,00*	Logistic supply	0.62
Smooth sides truck / easier to clean	0,16*	Limited addresses per truck	0.63

* Interventions included in total package of interventions for calculation of cost-effectiveness (interventions that can be implemented in short term and do not overlap considerably with other interventions)

Table 3 Interventions in the lairage stage and the corresponding net costs

Intervention	€ / pig	Intervention	€ / pig
Hygiene (stables, platform, rows)	0.16*	Closed compartments	0.01*
Herd status separation	0.05*	Adjusted loading platform	0.09*
One group per compartment	0.09*	Logistic supply	n.c.

n.c.; not calculated due to lack of information on input variables
*Interventions included in total package of interventions for calculation of cost-effectiveness (interventions that can be implemented in short term and do not overlap considerably with other interventions)

Table 4 Interventions in the slaughtering stage and the corresponding net costs

Intervention	€ / pig	Intervention	€ / pig
Automatic evisceration	0.15*	Omission of splitting head	0.00**
Adjusted scalding	0.05*	Testing serologically	0.25*
Hygiene	0.58*	Testing carcasses bacteriologically	0.22*
Decontamination	0.17	Adjusted meat inspection	0.05*
Guiding and packing rectum	0.13*	All pigs fasted before transport	-0.06*
Fine tuning equipment	0.10*	Logistic supply	n.c.

n.c.; not calculated due to lack of information on input variables
* Interventions included in total package of interventions for calculation of cost-effectiveness (interventions that can be implemented in short term and do not overlap considerably with other interventions)
** common practice in the Netherlands

The exact quantitative effects of separate interventions on the introduction and spread of *Salmonella* and the course of infection are very difficult to quantify precisely. Still it is known that a package of multiple interventions leads to a reduction of *Salmonella* prevalence (e.g. Bagger and Nielsen, 2001). Therefore, in this paper a stage has two options: implementing the package of interventions as described in Tables 1 to 4 in order to reduce the introduction and spread of *Salmonella* or not implementing any control measure. In the epidemiological simulation model, the effect of this package of interventions was set to result in a reduction of input variables type 1 and type 2 of the default values with 50% towards the minimum value. Besides, a sensitivity analysis was carried out in which the reduction is set to 20% and to 80%. The type 3 input variables, related to the design of the pork supply chain, did not change by interventions. A reduction of the value of an input variable leads to a lower risk for introduction or spreading of *Salmonella*.

2.2 Economic model

The economic model was based on the principles of the technique of partial budgeting, i.e. a quantification of the economic consequences of a specific change in farm or firm procedure (Boehlje and Eidman, 1984; Dijkhuizen et al., 1995). Hence, the basic situation is compared with an alternative situation. For the basic situation in each stage, a typical farm or firm is described. The alternative situation means that a package of interventions is implemented (see Tables 1 to 4). The partial budgets are calculated for each stage separately. The general format for a partial budget is made up of four categories: additional returns (AR), reduced cost (RC), returns foregone (RF) and extra costs (EC). The net costs are calculated by adding the costs minus the returns.

$$\text{Net costs} = (RF + EC) - (AR + RC) \qquad (1)$$

The separate categories are discussed briefly. Currently, there are no additional returns for selling *Salmonella* free animals or carcasses in the Netherlands. In some stages, additional returns can occur due to control of *Salmonella*. For instance in the finishing stage whereas interventions can lead to an increased daily weight gain, reduced feed conversion ratio or decreased veterinary costs due to an improved animal health. Up to now, no literature is available with quantification of these additional returns. Some control strategies will lead to reduced costs. For instance, a slaughterline with robots for evisceration needs fewer personnel and a farmer who does not feed pigs on the day before transportation saves costs for feed. No returns foregone are applicable to the included interventions. Hence, most interventions result mainly in extra costs due to investments and extra labour.

Most input data for the partial budgets of the interventions of the finishing stage were based on the Dutch Quantitative Information Animal Husbandry (Anonymous, 2001b). Other sources used were Lambooij (2002), specialised magazines for animal husbandry and meat industry (e.g. Anonymous, 2002a), web-sites of suppliers and personal communications with people working in the pork supply chain. Tables 1 to 4 show the interventions per stage and their corresponding net costs. The package of interventions includes not all suggested interventions, since some interventions overlap and some interventions are not feasible in practice yet. For all stages, interest rate was set at 6% and labour costs at 25 Euro per hour.

The calculations of the net costs are based on typical or average Dutch farms and firms. Note that the parameters of the model can be adjusted to reflect other type of farms or firms. For the finishing stage, the net costs in Euro per pig are calculated for a traditional specialised finishing farm with 2000 pig places (2 stables with 10 compartments each). For the transportation stage, an average truck transports 100 finishing pigs per ride and rides 12 trips per week. It is not taken into account that trucks may also be used for transportation of piglets, sows or other species. The slaughterhouse (including lairage and slaughtering) used for the calculation processes 600 pigs per hour and 1.5 million per year, which is quite common in the Netherlands. The lairage can accommodate 1800 pigs. In the basic situation the evisceration is executed by hand and the slaughterline is cleaned at the end of each working day. The carcasses are not decontaminated (e.g. by spraying lactic acid or steam over carcasses at the end of the slaughterline), since this is not allowed in the European Union for fresh meat. The possible effects on meat quality are not taken into account, since they are not known.

A summary of the net costs per stage used in further calculations is shown in Table 5.

Table 5 Net costs for a package of interventions per pig delivered in four stages

Stage	Net costs (€ / pig delivered)
Finishing stage	2.99
Transportation stage	0.65
Lairage	0.40
Slaughtering stage	1.47

Source: see Table 1 to 4

Because of the uncertainties about several input parameters for the partial budgeting, a sensitivity analysis was carried out to test the robustness of the conclusions. In the sensitivity analysis for each package of interventions the net costs were increased and decreased by 20%.

2.3 Research design

Each scenario included 2000 days and every week 10 groups of 100 pigs entered the model. In the default scenario none of the stages implemented interventions as suggested in section 2.1. In all alternative scenarios one or more stages intervened. A stage that implemented a package of interventions will be referred to as a stage with a low risk profile. For each scenario, the epidemiological model provided the prevalence and the economic model provided the net costs per pig.

The ultimate goal of implementing interventions is a reduction of the prevalence of contaminated carcasses. This reduction is a percentage and can not be expressed directly in monetary units. In order to combine the output of the two models, the principles of the technique of cost-effectiveness were used (Belli et al., 2001) to define a suitable parameter for comparison. The cost-effectiveness of a scenario per stage (CE_{stage}) was calculated by dividing the reduction in prevalence in a stage (ΔP_{stage}) by the change in net costs per pig for interventions in that particular stage (ΔC_{stage}). The cost-effectiveness of a scenario with respect to food safety of carcasses (CE_{chain}) was calculated by dividing the reduction of the prevalence at the end of the slaughterline (ΔP_{chain}) by the total net costs per pig for stages that implemented interventions (ΔC_{chain}). In formulas:

$$CE_{stage} = \Delta P_{stage} / \Delta C_{stage} \quad (2)$$

$$CE_{chain} = \Delta P_{chain} / \Delta C_{chain} \quad (3)$$

The evaluation of the cost-effectiveness in the pork supply chain is split into three parts. The first part is the evaluation of implementing interventions in one stage at the time. The cost-effectiveness for the stage that implemented the intervention package (CE_{stage}) and for the end of the chain (CE_{chain}) was calculated. Since the four stages finishing, transport, lairage and slaughter were included, this part included four scenarios. The second part is the calculation of CE_{chain} in case two, three or four stages implemented interventions, which resulted in twelve scenarios ($12 = 2^4 - 4$).

In practice, probably not all participants in a stage will intervene to reduce *Salmonella*, so the third part contained an evaluation of the effects on the prevalence per stage in case not all farms or firms within a stage implement interventions. The other stages are set to the default situation. This part does not deal with the net cost directly, but focussed on the prevalence at the end of the chain. The prevalence of all groups of 100 pigs that leave the chain as a chilled carcass was calculated with the epidemiological model. In this case, especially the percentage of groups with a high prevalence is interesting. The percentage of groups of carcasses above 1%, 2% and 15% is calculated for 11 scenarios, whereas in the first scenario no farm or firm in a stage implemented the package of interventions. In each subsequent scenario, the fraction of farms or firms that intervened was increased by 0.1.

3 Results

3.1 Cost-effectiveness of implementing interventions in one stage

Part one included the calculation of the cost-effectiveness of a package of interventions in one stage on the prevalence of *Salmonella* in that stage (CE_{stage}) and the cost-effectiveness of that package of interventions on the final prevalence of contaminated carcasses (CE_{chain}). The results are shown in Figure 2.

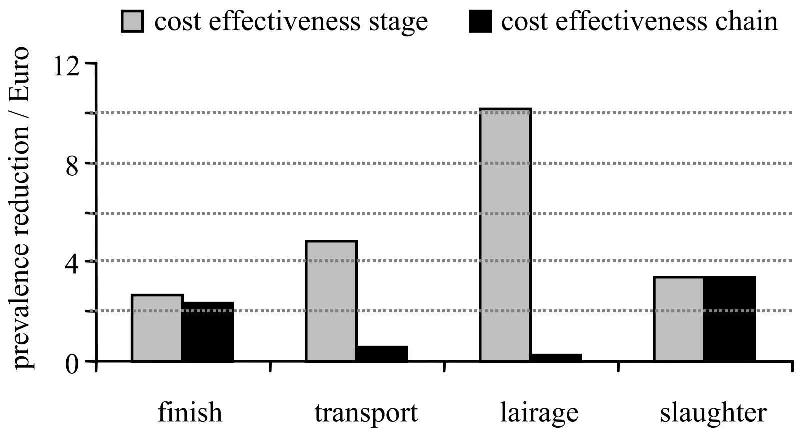

Figure 2 Cost-effectiveness of a package of interventions in one stage related to the *Salmonella* prevalence in that stage (CE_{stage}) and on the final prevalence on the carcasses (CE_{chain}).

CE_{stage} varied between 2.6%/Euro in the finishing stage to over 9%/Euro in the lairage. Hence, regarding the stages separately, it is most cost-effective to implement a package of interventions in the lairage. However, CE_{chain} in the lairage is only 0.2%/Euro, indicating that if operating procedures at slaughter are not improved, the improvement in the lairage is largely cancelled out. For the prevalence of contaminated carcasses, the CE_{chain} appeared to be the highest in the slaughtering stage and second highest in the finishing stage.

3.2 Cost-effectiveness of implementing interventions in multiple stages

In the second part of the research design, all combinations of stages with default and low risk input values are tested. Figure 3 shows the results of the epidemiological and the economic model. Each dot in Figure 3 is a result of a scenario and the results of part one are also included. The costs per pig are calculated by adding the net costs per stage that is at low risk. For instance, if the stages transport and slaughter are set to low risk, the net costs per pig in the chain are 2.12 Euro (0.65 Euro + 1.47 Euro; see Table 5). The average prevalence of contaminated carcasses is 1.5% with a standard deviation of 1.9%.

Figure 3 can be divided into three groups based on the type of scenarios. The first group is in case the net costs in the pork chain to reduce the *Salmonella* prevalence are less than 1 Euro/pig. These points in Figure 3 are derived from scenarios whereas no stage intervened or the transportation and/or lairage implemented interventions. The reduction of the prevalence of contaminated carcasses is small. The second group of scenarios in Figure 3 is between 1 and 4.5 Euro/pig, whereas at least one of the stages finishing or slaughter intervened. The average prevalence fluctuated around 2%. The third group with the net costs between 4.5 and 6 Euro/pig is derived from scenarios with the finishing and slaughtering stage implemented interventions. A combination of these two stages showed most effective to reduce the prevalence of contaminated carcasses.

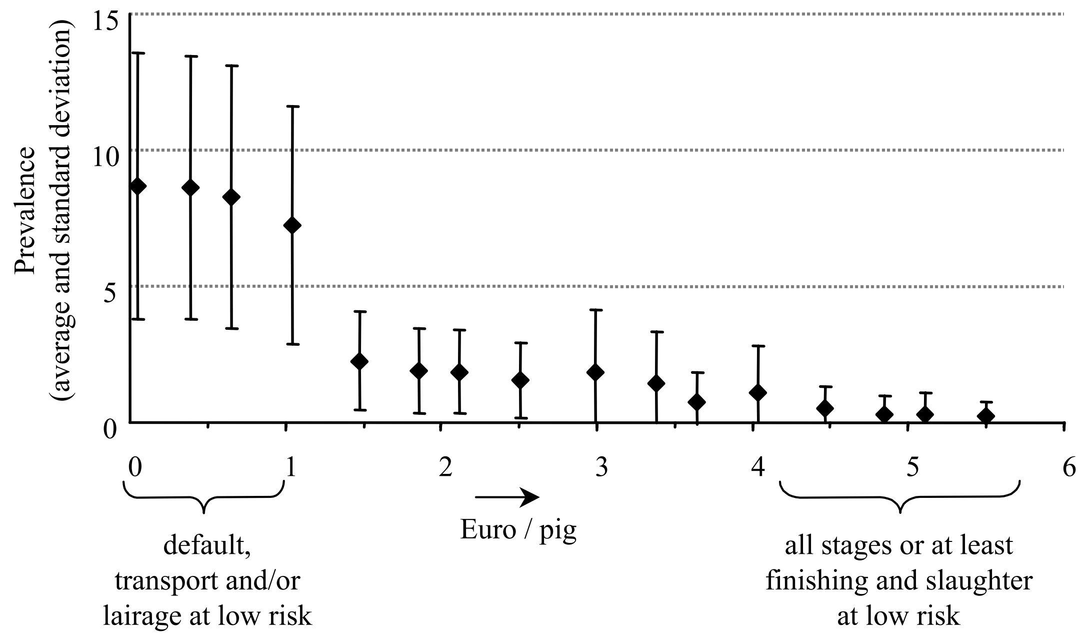

Figure 3 Prevalence (average and standard deviation) of contaminated carcasses and the costs per pig in Euro for 16 scenarios

In the global market for pork, Denmark is one of the competitors for the Netherlands. The Danish pork industry claims that the average prevalence of their carcasses is 2% (Anonymous, 2002b). The global interest for *Salmonella* in pork is emerging and countries may include the issue in the import requirements. In that case, a low *Salmonella* prevalence can result in a price premium. Therefore, in case the maximum average prevalence is set to 2%, implementation of interventions in the finishing and slaughter stage are essential. Note that these scenarios are based on the assumption that if a stage is at low risk, all farms and firms are expected to intervene. Another approach can be that the participants of the pork supply chain agree on a maximum amount of money that should be invested per pig in the chain, for instance 3 Euro. In that case there are 5 scenarios that result in a reduced prevalence (the four scenarios that cost less than 1 Euro/pig are not interesting because of the limited reduction of the prevalence) and fulfil the demand of a maximum investment of 3 Euro per pig.

3.3 Partial or total participation per stage

The third part of the research design explored what the impact will be in case not all farms or firms within a stage implement interventions. The largest effect was seen in the finishing stage and these results are given in Figure 4. This Figure gives the percentage of groups of carcasses that are above a prevalence level of 1%, 2% and 15%.

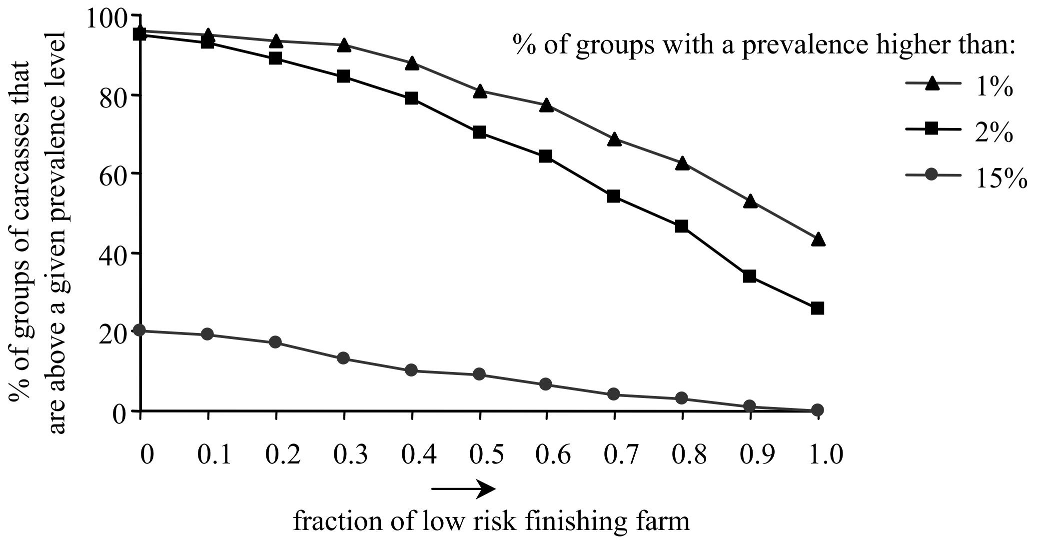

Figure 4 Percentage of groups of carcasses that are above a prevalence level of 1%, 2% and 15% in case no finishing farms are at low risk to all finishing farms are at low risk

From Figure 4 can be seen that the net effect of interventions at the finishing stage on the prevalence of contaminated carcasses increases in case more groups of pigs are raised in a low risk finishing farm. In the stages transport, lairage and slaughter the net effect of interventions in a stage is more or less linear.

3.4 Sensitivity analysis

The sensitivity analysis of the effects of interventions on the epidemiological model and on the net costs in the economic model showed that the trend of the outcome did not change. In case the net costs per stage were increased or decreased, the actual value of the cost-effectiveness changed, but ran parallel with the results of the scenarios in part one and two. Therefore, the trend of outcomes remained unchanged. When the impact of the package of interventions on the input values of the simulation model was set to a reduction of 20% instead of 50%, the effect on the prevalence within a stage and on the prevalence of contaminated carcasses was minor. Only in the slaughtering stage, there was still a clear effect of the interventions and in the finishing stage, a small effect was evident. The cost-effectiveness of the package of interventions was small. The scenarios with 80% reduction showed results comparable with the results of the standard simulation only more extreme. Therefore, the trend of outcomes remained unchanged.

Hence, the sensitivity analyses showed that the ranking of scenarios is robust with respect to the economic evaluation since changes in the economic evaluation did not change the tendency of the results.

4 Discussion

In this paper, we presented a method to evaluate the cost-effectiveness of several scenarios to reduce *Salmonella* in the pork chain. A complete insight however, was hard to obtain due to limited information on the input data and the scarce quantitative information about the expected improved performance in a stage due to the interventions. Especially the input data for the partial budgets for the stage lairage and the stage slaughter were difficult to collect, since some information is subject to business sensitiveness. Adding the costs of the separate interventions may result in a slight overestimation of the costs, since some interventions may need similar investments. However, the aim of the paper was to explore the most promising scenarios to reduce the prevalence of contaminated carcasses. The sensitivity analysis confirmed the robustness of the conclusions.

The reduction of *Salmonella* in the pork chain to a level whereas the average prevalence plus standard deviation is below 2%, can be achieved when at least 4.5 Euro per pig is invested. In the event that all packages of interventions from finishing through slaughtering are implemented, the total net costs per pig are 5.5 Euro, which are about 4% of the total costs for a pig in those stages. This is relatively expensive, but it has to be stated that almost all interventions in order to reduce *Salmonella* in the pork chain are also effective in reducing other pathogens. In that respect, the costs to reduce the prevalence should be divided over more pathogens than only *Salmonella*. In case of an improvement of the food safety of pork, the incidence of human salmonellosis should decrease, which results in a decrease of the societal costs of human salmonellosis. In other words, the direct benefits are outside the pork supply chain, i.e. for society. The indirect benefits that are not included in this paper are issues like trust of consumers, better image of pork and a strengthened position on the global market for pork.

Most scenarios in this paper are based on the assumption that all farms or firms within a stage will implement the suggested intervention measures. However, some farms and firms already intervened in order to increase the food safety of their product. The objective of the paper was to explore cost-effectiveness of intervention scenarios. The results are a basis for further research with a more detailed approach. In the paper, the suggested interventions are equal for each farm or firm in a particular stage. In practice, the interventions that should be implemented and their cost-effectiveness depend heavily on the risk profile of the farm or firm. Since all farms and firms have their own weak points with respect to the introduction and spread of bacteria, it is not recommendable to enforce fixed interventions to stages. Slaughter- and process plants have the obligation to introduce the HACCP (Hazard Analysis of Critical Control Points) system. The *Salmonella* issue should be included. Since the ultimate goal is to improve food safety, performance standards for a maximum prevalence or a maximum average prevalence of *Salmonella* have to be determined. For the primary stages an approach like HACCP with determined limits, whereas a farm or firm can focus on its specific weaknesses, is probably most cost-effective and expected to reach a higher level of food safety. As calculated in this paper, some interventions in the chain are expensive and therefore maybe not worth to make mandatory for every chain participant.

Up to now, the (pre-)harvest stages of the pork supply chain can not ensure a zero prevalence of contaminated carcasses. So, the next stages (processing, storage at retail and storage and preparing the pork by the consumer) are also important. For instance, the consumer can reduce the risk of food-borne salmonellosis by cool storage and throughout heating of the pork and by avoiding cross-contamination in the kitchen (Gorman et al., 2002). Nevertheless, by reducing the prevalence of contaminated carcasses, the risk for the consumer should be decreased since less contaminated pork enters the consumers' kitchen.

5 Conclusions

The objective of the paper was to explore the cost-effectiveness of interventions against *Salmonella* in the pork supply chain. The first conclusion is that with respect to the prevalence reduction in the *stages*, the lairage stage seems to be most cost-effective. The second conclusion is that the most cost-effective strategy for the pork supply *chain* is to implement interventions in the first place in the slaughterhouses and also in the finishing farms. The third conclusion is that the cost-effectiveness is reduced in case not all farms or firms within a particular stage participate in reducing the prevalence of *Salmonella*. The most effective strategy with respect to the reduction of *Salmonella* will be to include the transportation and lairage in the *Salmonella* control program, since these stages may become more important when the largest problems are solved in the finishing and slaughter stage. The results of this paper give the first insight in the promising scenarios. In further research, these scenarios have to be examined in more detail and can subsequently put into practice.

Acknowledgements

The research was co-financed by Agro Chain Competence in the Netherlands, Nutreco and Nedap Agri.

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Chapter 5

Economic evaluation of control of Salmonella in the pork supply chain

Abstract

A possible regulation to improve food safety of pork with respect to Salmonella is to define a maximum acceptable prevalence (MAP) of contaminated carcasses per slaughtering firm. For instance by defining a MAP for batches of carcasses for fresh meat-products and a MAP for batches for processed meat products. The revenues for batches of carcasses that exceed a MAP are likely to be lower than for batches below the MAP. With respect to Salmonella in the pork chain, the finishing and slaughtering stages are most important to reduce the prevalence of contaminated carcasses. To control Salmonella, these stages can choose among four different control strategies: default, preventive control, corrective control and total control.

A stochastic simulation model calculated the prevalence of contaminated carcasses for each control strategy. The total costs per strategy are calculated using an economic model based on partial budgeting. Results show that when testing costs are high, preventive control measures are preferable to control Salmonella. Segmentation of batches of carcasses based on their prevalence increases food safety. However, investments in control do not always result in a reduction of the average prevalence. Under our assumptions, total control (preventive and corrective) in the pork chain is not cost-effective.

1 Introduction

About 25% of the 50.000 Dutch annual cases of human salmonellosis is caused by *Salmonella* serotypes occurring in pigs (Van Pelt and Valkenburgh, 2001). To control the food safety of pork with respect to *Salmonella* contamination, the entire pork supply chain has to be involved (Berends, 1998; Lammerding and Fazil, 2001). The basic end-product of the pork chain is a chilled carcass at the slaughterhouse. Therefore, the first focus should be on the reduction of prevalence of carcasses contaminated with *Salmonella* at the end of the slaughterline.

Presently, there is no price difference between carcasses that are free of *Salmonella* and carcasses contaminated with *Salmonella*. In the (near) future, this is likely to change due to the increasing pressure on food safety demands in general and on *Salmonella* in particular. Market and authorities will formulate minimum standards with respect to acceptable levels of *Salmonella* contamination of food products. To meet these standards, control measures have to be implemented in the supply chain. Since the implementation of control measures results in increased production costs, insight is needed into the cost-effectiveness of these measures. On the other hand, in case the implemented control measures lead to an improvement of food safety, there are also indirect revenues related to the control measures. These revenues are e.g. societal revenues due to less human cases of food borne diseases and revenues for the pre-harvest part of the supply chain due to a better market position and a better price for high-grade products.

In practice, some countries already implemented a control system based on prevalence. For instance, the Danish pig production do have a price differentiation system for finishing farms that is based on the so-called 'serological *Salmonella* index' with three levels (1, 2 and 3). Level 1 is the level with the lowest *Salmonella* prevalence. Each month a finishing farm is assigned to one of these levels based on serological samples of their pigs at the slaughterhouse (Alban et al., 2002). Farms in level 2 and 3 get a penalty of respectively 2 % and 4% of the value per pig slaughtered (Nielsen et al., 2001). This system can be seen as a variant of a system with MAP's, although the price differentiation is not based on segmentation of batches but meant to motivate finishing farms to reduce the average *Salmonella* prevalence.

The aim of the paper was to explore the economic consequences of different regulation principles (like predefining a maximum acceptable prevalence) for variable control strategies in the pork supply chain to reduce the prevalence of carcasses contaminated with *Salmonella*.

2 Theoretical background

2.1 Maximum Acceptable Prevalence on the long-term

Since Salmonella is ubiquitous in nature, zero prevalence at carcass level is virtually impossible. Therefore, to improve food safety, a maximum acceptable prevalence (MAP) of contaminated carcasses has to be set. There are two principles for the MAP. The first principle is the long-term principle, in which the average prevalence of contaminated carcasses in e.g. a year should not exceed the predefined MAP for the long-term ($MAP_{longterm}$). Consequently, the level of contaminated carcasses that is used for human consumption over a year is controlled. In order to ensure an acceptable level of food safety, the $MAP_{longterm}$ can be seen as a kind of license to produce. In other words, farms or firms that are not able to reach an average prevalence level below $MAP_{longterm}$ are not allowed to produce or they loose their certificate to produce for a specific market. In Figure 1, a hypothetical distribution of the average prevalence per farm or firm in one stage is presented. The horizontal axis presents the average prevalence of batches over e.g. a year per farm or firm. The vertical axis presents the frequency of farms or firms in a stage with the prevalence stated on the horizontal axis. In Figure 1, the frequency of farms or firms with a prevalence of zero is A. The hatched part of the distribution presents the fraction of farms or firms that exceed the $MAP_{longterm}$.

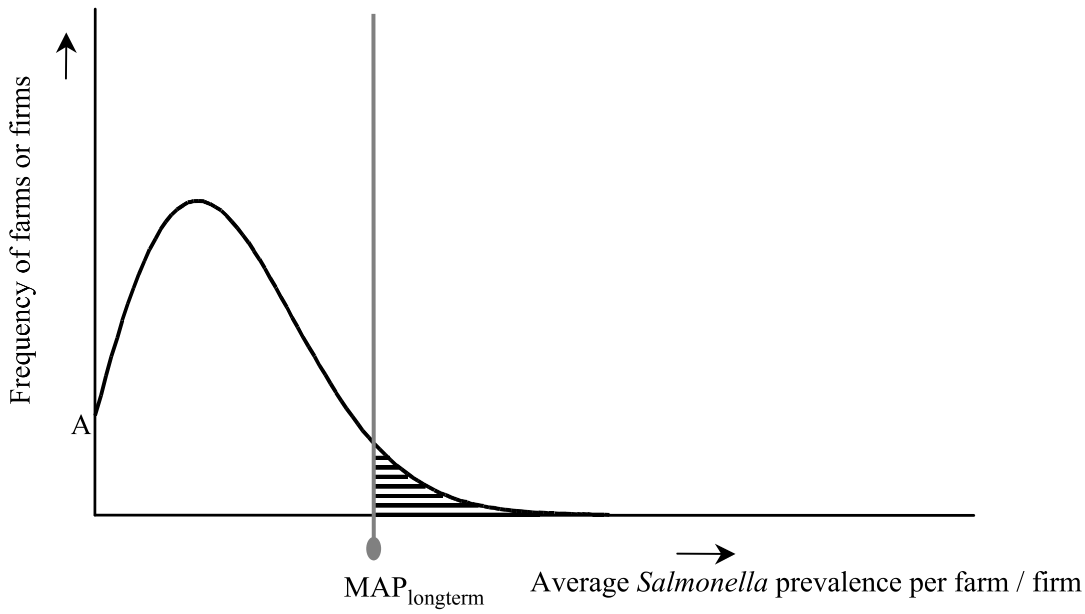

Figure 1 Hypothetical distribution of average *Salmonella* prevalence per farm or firm in one stage over a longer period ($MAP_{longterm}$ = Maximum Acceptable Prevalence on the long-term)

2.2 Maximum Acceptable Prevalence per batch

The perspective of $MAP_{longterm}$ gives no insight in the distribution of batches with contaminated carcasses within the given time. In other words, it is possible that in certain time periods the prevalence of batches is very high. Therefore, a second principle is defined that deals with the average prevalence per batch of carcasses (e.g. per batch of 100 carcasses or per batch carcasses originated from one finishing farm) which should not exceed a predefined prevalence. This principle also guarantees a maximum number of contaminated carcasses per year, but additionally it prevents that highly contaminated batches find their way to the consumer.

A high prevalence batch causes a higher risk for food borne diseases when the batch is sold for fresh meat products than when the batch is processed to cooked, salted or fermented meat products. These processing steps are in fact some kind of decontamination since these processes largely eliminate *Salmonella* bacteria. From this point of view, the prevalence per batch determines the purpose of the batch. Batches for fresh meat should have a lower prevalence target than batches meant for further processing. However, also for processed pork products, control is essential since the preservation of processed pork products depend on the initial bacterial load (Lo Fo Wong et al., 2002). Consequently, two MAP_{batch} values can be distinguished: $MAP_{batch\text{-}fresh}$ for fresh pork products and $MAP_{batch\text{-}process}$ for production of processed pork products (cooked, salted or fermented). With respect to food safety, the $MAP_{batch\text{-}fresh}$ should be equal or lower than $MAP_{batch\text{-}process}$. Batches that exceed the $MAP_{batch\text{-}process}$ are not suitable for regular processing and are used for low-grade products or pet food. Figure 2 presents three hypothetical distribution functions for the prevalence of contaminated carcasses per batch. Each distribution represents the frequency of the prevalence of batches contaminated carcasses of one farm or firm. Note that Figure 2 is not directly comparable with Figure 1. Figure 2 presents the distribution of batches contaminated carcasses within a farm and Figure 1 presents the distribution of average prevalence of farms or firms within a stage over a certain period.

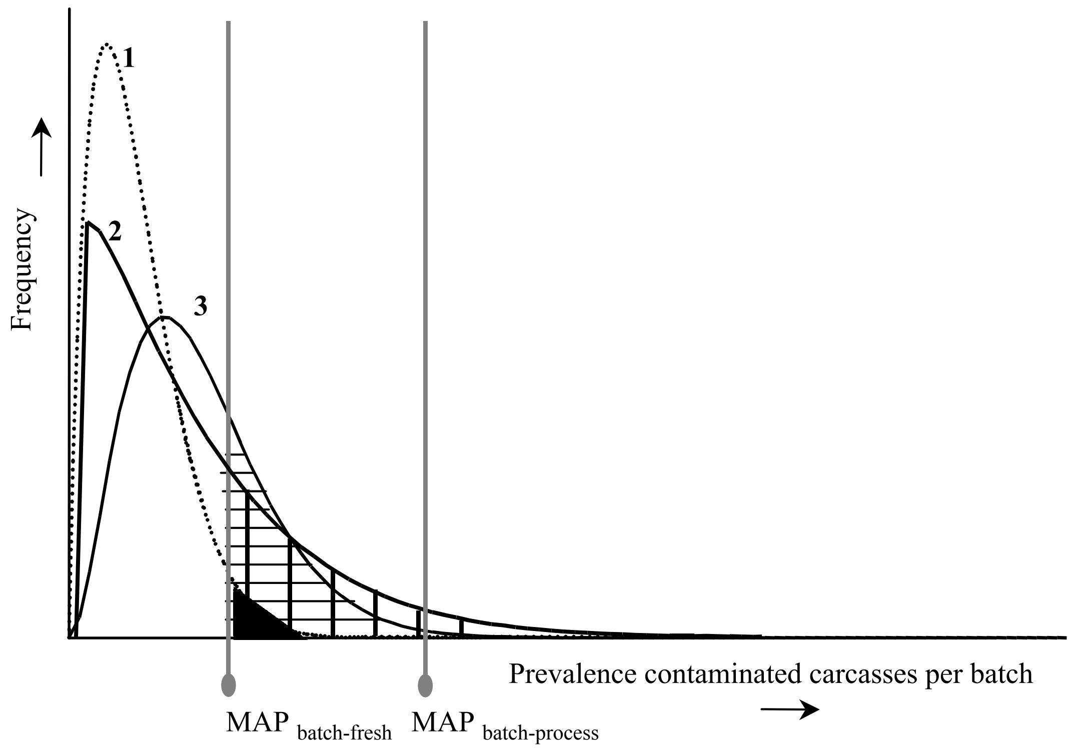

Figure 2 Three hypothetical distributions of the prevalence of contaminated carcasses per batch per farm or firm

In distribution 1, only a few batches exceed the $MAP_{batch\text{-}fresh}$ (the black surface under distribution 1). These batches do not exceed $MAP_{batch\text{-}process}$ and are suitable for regular processing. Distribution 2 shows much more batches that exceed $MAP_{batch\text{-}fresh}$ (the vertical hatched surface under distribution 2) and several batches that exceed $MAP_{batch\text{-}process}$. Finally, distribution 3 has almost no batches that exceed $MAP_{batch\text{-}process}$, but relatively many batches that exceed $MAP_{batch\text{-}fresh}$ (the horizontally hatched surface).

2.3 Segmentation of batches and the revenues per segment

In the Netherlands, there is no price differentiation with respect to the level of contamination of batches. However, it is obvious that a price differentiation system is a logical consequence of establishing MAP's by either market or authorities. When both $MAP_{batch\text{-}fresh}$ and $MAP_{batch\text{-}process}$ are determined, three segments of carcasses can be distinguished: batches for fresh meat products, batches for processed meat products and batches for low-grade products. To be able to maintain the system with MAP's, a testing procedure is required to assign batches to a segment. For each segment, the carcasses may yield different revenues. The net revenues for the segment of fresh meat products (*Rf*) are higher than or equal to the net revenues for the segment of processed meat products (*Rp*), since there are no restrictions for the carcasses in the fresh meat segment. Comparably, the *Rp* are higher than or equal to the net revenues of batches in the segment for low-grade products (*Rr*). Figure 3 presents the principles of segmentation of batches.

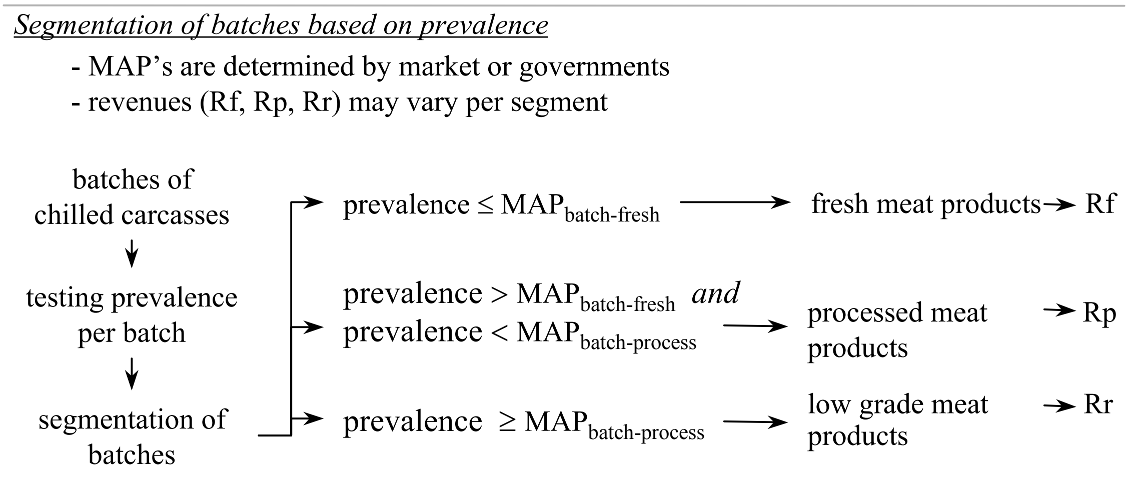

Figure 3 Segmentation of batches and corresponding revenues based on prevalence

2.4 Prevalence reduction strategies

A prevalence reduction strategy means implementation of control measures in one or multiple stages in the pork chain. The implementation of control measures results in increased costs. Control can be preventive or corrective. Preventive control measures prevent the introduction or spread of *Salmonella* in the pork chain. The costs for preventive control measures are fixed, since the measures are carried out continuously and do not depend on the current *Salmonella* prevalence. Corrective control measures also reduce introduction or spread, but these measures are implemented temporarily and the farm or firm determines when and how long the corrective control measures are implemented. Therefore, the farm or firm have to test the prevalence of the batches it produces and should determine a so-called threshold prevalence. When the batch tested exceeds this threshold prevalence, the farm or firm will temporarily implement corrective measures. Note the difference between a threshold prevalence (determined by the farm or firm, no direct effect on revenues) and the MAP (determined by market or authorities with a possible effect on the revenues). The costs for corrective control measures are variable, because corrective control is temporarily. The duration of carrying out corrective measures is also determined by the manager of the farm or firm. In conclusion, the total duration of the implementation of corrective measures at a farm or firm depends on the threshold prevalence and the determined duration of implementation after this threshold is exceeded.

If the prevalence of batches is always below the predefined threshold prevalence, no corrective measures have to be implemented. A testing procedure is necessary to check whether the true prevalence exceeds the threshold prevalence. The costs for testing depend on the characteristics of the test, the frequency of testing and the percentage of animals tested. Several control measures can be implemented as a preventive and as a corrective measure. For example, if a farmer disinfects the compartments continuously, it is a preventive measure and in case this procedure is carried out only after batches that exceed the threshold prevalence, it is a corrective measure.

Each stage can choose among four different control strategies as shown in Table 1. In the default situation (D) no control measures are implemented. In the preventive situation (P) the stage implements a package of preventive measures, but no corrective measures. In the corrective strategy (C), only corrective measures are implemented and in the total strategy (T) both preventive and corrective measures are implemented.

Table 1 Four strategies for each stage in the pork chain

Strategy	Preventive measures	Corrective measures
D: Default	No	No
P : Preventive	Yes	No
C: Corrective	No	Yes
T: Total	Yes	Yes

2.5 Testing procedures

In each stage, samples can be taken to measure the prevalence. However, standard sampling of pigs in the transportation stage or in the lairage is not practical and labour intensive. Especially regular serological sampling cannot be executed in these stages. The stages finishing and slaughtering are more suitable for testing. Serological sampling to determine the prevalence of finishing farms is possible in the finishing stage or at the slaughterhouse, since the serological status does not change after pigs leave the finishing farm. The *Salmonella* prevalence of pigs in the finishing stage can also be determined by bacteriological testing of faecal samples in the finishing farm. Faecal samples in the slaughterhouse are less useful since the pigs may also become infected and start shedding during transportation or in the lairage (e.g. Lo Fo Wong et al., 2002). With respect to food safety, the prevalence of contaminated carcasses that is determined by bacteriological testing of carcasses, is most important.

2.6 Costs and revenues

The maximum revenues in the chain are achieved in case there are no costs for control or testing and all batches are in the best *Salmonella* segment, yielding the highest revenues. However, this is not realistic. To increase the percentage of batches in the best segment, costs for control and testing are necessary. The costs are calculated as additional costs compared to the default situation where no control measures are implemented. In case batches of carcasses are in the segment of processed or low-grade meat products, the revenues are reduced. These reductions of revenues, the so-called revenues forgone can be seen as additional costs.

The total costs in the chain for each chain control strategy compared to the ideal situation (maximum revenues, no costs) are defined as the revenues forgone in that chain control strategy added by the costs for control measures and testing.

Eq. 1 presents the calculation of total costs per pig for each chain control strategy ($TC_{strategy}$):

$$TC_{strategy} = (Rf - (Bf * Rf) - (Bp * Rp) - (Br * Rr)) + Cp + Cc + Ct \quad (Rf \geq Rp \geq Rr) \qquad (1)$$

whereas

- $TC_{strategy}$: total costs of a chain control strategy compared to ideal situation
- Rf: Net revenues for batches with prevalence $\leq MAP_{batch\text{-}fresh}$
- Rp: Net revenues for batches with prevalence $\geq MAP_{batch\text{-}fresh}$ and $\leq MAP_{batch\text{-}process}$
- Rr: Net revenues for batches with prevalence $\geq MAP_{batch\text{-}process}$
- Bf: Fraction of batches with prevalence $\leq MAP_{batch\text{-}fresh}$
- Bp: Fraction of batches with prevalence $\geq MAP_{batch\text{-}fresh}$ and $\leq MAP_{batch\text{-}process}$
- Br: Fraction of batches with prevalence $\geq MAP_{batch\text{-}process}$
- Cp: Costs for preventive measures in the chain
- Cc: Costs for corrective measures in the chain
- Ct: Costs for testing (monitoring) in the chain

Currently, there are no differences in net revenues for batches with high or low prevalence, hence, $Rf = Rp = Rr$. To minimise the $TC_{strategy}$ for the entire chain, it is possible that one or multiple stages have relatively high costs and do not receive additional revenues for these costs. In that case, the costs and revenues have to be redistributed over the stages in the chain to motivate all stages to improve the overall chain performance. The redistribution is a complex process, which is not included in this study.

Besides the $TC_{strategy}$ in the chain through harvest, there are additional revenues due to an improved market position. Also for society, additional revenues occur. The main goal to reduce the prevalence is to improve food safety of pork products with respect to

Salmonella. If food safety is improved, the number of human cases of salmonellosis (in)direct caused by pork is reduced. Less human cases lead to a reduction of the societal costs for hospitalisation, reduced labour productivity and premature death. Additional returns for society are the reduced costs for human salmonellosis. These indirect revenues (decrease in societal costs and improved market position) are not included in the calculation of the total costs, although they do play a role in practice.

3 Materials and methods

3.1 Research design

Scenario studies were carried out in order to get insight in the cost-effectiveness of different chain control strategies in the pork chain to reduce the prevalence of contaminated carcasses. For this purpose, an epidemiological simulation model was designed to calculate the prevalence of contaminated carcasses and the percentage of time the stage implements corrective measures. The epidemiological model includes the stages finishing, transport, lairage and slaughter. An economic model calculated the net costs and revenues. These models are described in the following sections. The combination of the results of the epidemiological and economic model results in the cost-effectiveness. A scenario includes all chain control strategies and for each chain control strategy three runs with the epidemiological model are executed. A chain control strategy means that each stage in the chain executes a control strategy as stated in Table 1. Since two stages (finishing and slaughtering) are included in this study, a scenario includes 16 chain control strategies. Section 3.2 presents the motivation for choosing for these two stages. Each run consists of 1200 days whereas 200 pigs enter the finishing stage on a weekly basis. A pig remains in the model for 116 days (113 days in the finishing stage and then going to the succeeding three stages). Figure 4 presents the research design.

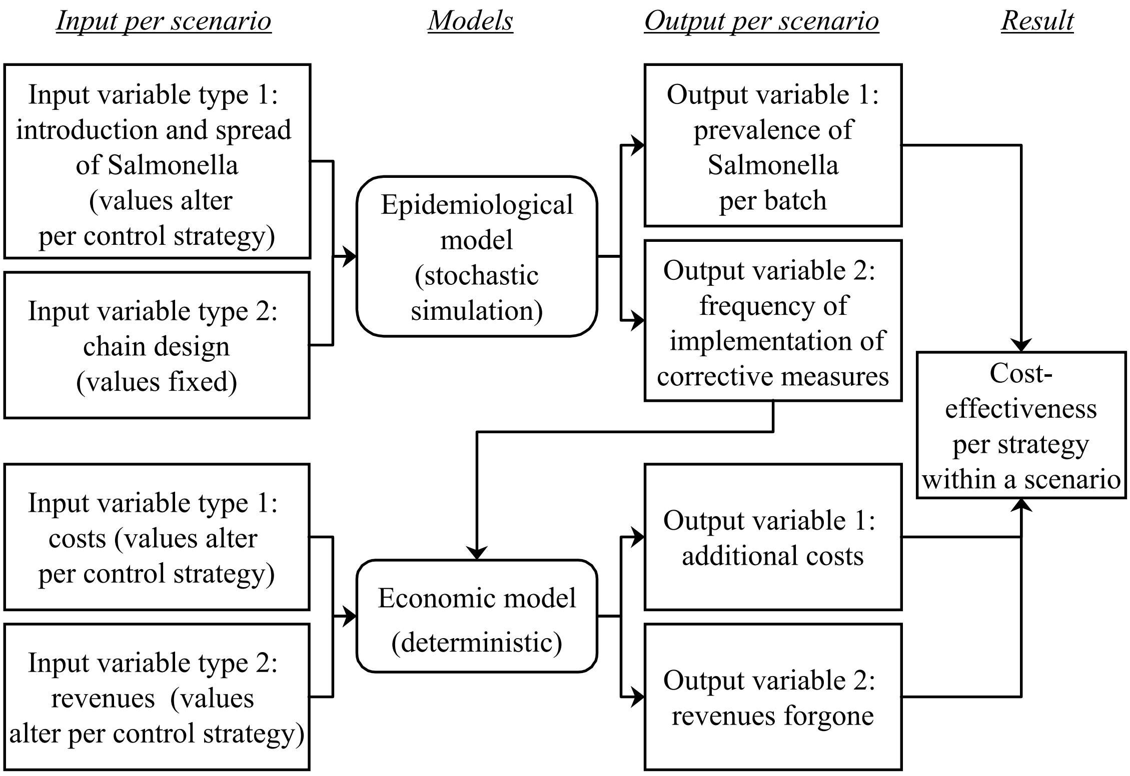

Figure 4 Research design (calculation approach per scenario)

For executing the scenarios, the applied testing procedure came down to a serological test for the finishing stage and a bacteriological test for the carcasses at the slaughtering stage. The serological test is executed at the slaughterhouse, but the costs are attributed to the finishing stage since the results of the test determine whether the finishing stage should implement corrective measures. For the serological tests all individuals in a batch were tested. The bacteriological test is expensive (€ 20 per test) and it is not feasible to test all individuals. In this paper a fraction of the individuals per batch is tested. For example, when 10% is tested the costs are € 2 per individual. The sensitivity of the serological test is set at 95% and the specificity at 98%. For the bacteriological test, the sensitivity is set at 98% and the specificity at 99.9% (personal communication H. van der Heijden, Animal Health Service, the Netherlands). The sensitivity of a test reflects the probability that a positive sample is tested as positive. The specificity of a test reflects the probability that a negative sample is tested as negative. Since test results are not available immediately and the production process can not be stopped to wait for the results, corrective measures will often concern the batch(es) that are produced after the batch that exceeded the threshold prevalence. The threshold prevalence for the finishing stage is set at 10%. A serological zero prevalence is not feasible. When the threshold prevalence was exceeded, the stage implemented corrective measures for five succeeding days. The threshold prevalence for the slaughtering stage was set at 2%. When this prevalence was exceeded, the stage implemented corrective measures for 1 day.

3.2 The epidemiological simulation model

A stochastic state transition model was used to simulate the epidemiological effects of control measures in the pork chain on the prevalence of *Salmonella* in the separate stages. The modelling approach is based on the SIR-model (e.g. De Jong, 1995). In the model, groups of 100 pigs move through the pork chain. *Salmonella* free pigs may become infected with *Salmonella*. After being bacteriologically positive, pigs become serologically positive. After some time, a positive pig may become bacteriologically and serologically negative again. The model calculates the serological and bacteriological prevalence of each group at the end of each stage. The serological prevalence of a group of pigs does not change after the finishing stage. The definition used for a bacteriological positive carcass is that surfaces of the carcass or organs for human consumption are contaminated with *Salmonella* at the end of the slaughterline.

The model has two types of input variables (see also Figure 4):

1. input variables related to the introduction and spread of *Salmonella*, e.g. probability that visitors introduce the bacteria, probability that a carcass becomes contaminated by the equipment in the slaughterline, and probability that an infectious pig or contaminated carcass infects or contaminated another pig or carcass, both directly as indirectly by vectors such as brooms, knives etc. These variables can alter due to preventive or corrective measures.
2. input variables not directly related to the introduction and spread of *Salmonella* such as variables related to the design of the pork chain, e.g. sojourn time in each stage. These variables do not alter due to preventive or corrective measures.

The exact quantitative effects of separate measures on the introduction and spread of *Salmonella* are very difficult to quantify precisely. In the model, the effect of a strategy was set to result in a reduction of related input variables of type 1 from the default values towards the minimum value. Based on Van der Gaag et al. (2003) the preventive measures result in a 50% reduction of the input variables and during the implementation of corrective measures, these variables are set to the minimum value.

All possible combinations with four stages, four strategies and six economic variables (see section 3.3) lead to over thousands of runs. To reduce the number of chain strategies, a pre-test is carried out. In the pre-test, scenarios are executed where no preventive measures are implemented in the chain, but only corrective measures in one stage at the time. The pre-test included per stage three scenarios with different threshold prevalences. Based on the results of the pre-test, the stages finishing and slaughtering are selected to execute the scenarios. Preventive measures in transport and lairage will reduce the increase of infected pigs in these stages. However, measures in the stages transport and lairage have less effect on the reduction of the prevalence of contaminated carcasses than measures in the stages finishing and slaughtering (see also Van der Gaag et al., 2003b). Therefore, only the stages finishing and slaughtering are included in this study.

3.3 The economic model

The calculation of the net costs for the preventive measures is based on the technique of partial budgeting (Boehlje and Eidman, 1984; Dijkhuizen et al., 1995). For each stage, the default situation without implemented measures is compared with an alternative situation with preventive or corrective measures. The additional and reduced costs and the additional and reduced returns are calculated for each measure based on e.g. Quantitative Information Animal Husbandry (Anonymous, 2001). The calculations for the finishing stage are based on a standard specialised finishing farm with 2000 pigs. For the slaughtering stage, the calculations are based on a standard slaughterhouse that slaughters 1.5 million pigs a year.

To compare the net costs among the different chain strategies, the unit for the net costs for the finishing stage is daily costs per group of 100 pigs and for the slaughtering stage costs per pig slaughtered.

We defined a package of *Salmonella* reducing measures per stage for each of the strategy of Table 1. The strategy Default implements no measures; consequently strategy D has no *Cp* and *Cc* (see Equation 1). The costs for strategy T are divided in fixed costs due to implementation of preventive measures (*Cp*) and variable costs that are spent only during implementation of the additional corrective measures (*Cc* per time unit). The total duration that the stages implemented corrective measures are a result of the epidemiological model which is used as input for the economic model to calculate the final *Cc* per chain control strategy. Tables 2 and 3 present the costs for the control strategies in the finishing and slaughtering stage.

Table 2 Net costs for the strategies in the finishing stage in Euro[1]

	Costs (€)	Strategy C (only corrective)	Strategy P (only preventive)	Strategy T (both prev. and corr.)
Adding acid to water system[2]	1,73	*		
Wet feed[2]	1,45		*	*
Hygiene related to spread:				
- Closed fences between pens	0,01		*	*
- Separate brooms etc.	0,33	*	*	*
- Disinfecting compartments	0,12	*	*	*
Hygiene related to introduction:				
- Hygiene corridor	0,40		*	*
- Cleaning silos	0,25	*	*	*
- Rodent control	0,07	*	*	*
Fasting before transport	-0,09	*	*	*
Separate delivery room / building	0,26	*	*	*
Antibiotic cure	0,07	*		*
Extra daily cleaning and disinfecting	0,08			*
Special clothing per compartment	0,40	*		*
Total costs in Euro / 100 pigs / day[3]:		€ 3.14	€ 2.80	€ 2.80 (prev.) + € 0.55 (corr.)

[1] the costs may slightly differ from the calculated costs in Chapter 4 due to updated information
[2] basically the same measure, acidifying of water is on short term realisable
[3] i.e. the costs per pig delivered from finishing = (costs per 100 pigs per day) /(100 pigs * 113 days)

Table 3 Net costs for the strategies in the slaughtering stage in Euro[1]

	Costs (€)	Strategy C (only corrective)	Strategy P (only preventive)	Strategy T (both prev. and corr.)
Hygiene improvements:				
- Related to employees	0.04		*	*
- Related to slaughterline.	0.50	*	*	*
Automatic evisceration	0.15		*	*
Guiding and packing rectum	0.13		*	*
Adjusted meat inspection	0.03		*	*
Fine tuning equipment	0.10		*	*
All fasting before transport	-0.06	*	*	*
Scalding above 62°C	0.05		*	*
Extra personnel for secure hand work	0.45	*		
Additional cleaning end of the day	0.39	*		*
Total costs in Euro / pig slaughtered:		€ 1.28	€ 0.94	€ 0.94 (prev.) + € 0.39 (corr.)

[1] the costs may slightly differ from the calculated costs in Chapter 4 due to updated information

The net revenues of batches of carcasses depend on the prevalence of the batch. As stated in section 2, different levels of MAP can be distinguished. Table 4 presents the input variables for the calculation of the net revenues of the batches. The costs for testing depend on the sample size and the type of test. In addition, for strategies where no corrective measures are included, a testing procedure is necessary to determine the revenues for the batches. For this testing procedure, a smaller sample size is sufficient and the costs are € 0.20 per individual. These testing costs are not included in case there is another testing procedure in the chain control strategy included. Equation (1) is used for the calculation of the total cost in the chain per chain control strategy.

Table 4 Additional variables and their values used in the economic model

Variable	Unit	values used
$MAP_{batch-fresh}$	%	2, 5, 10, 20, 30
$MAP_{batch-process}$	%	5, 10, 20, 30, 100
$MAP_{longterm}$	%	1, 2, 4, 5
Costs for testing per pig	€	0.2, 0.5, 1, 2, 4
Revenues per carcass for batches with prevalence ≤ $MAP_{batch-fresh}$	€	150
Revenues per carcass for batches with $MAP_{batch-fresh}$ < prevalence ≤ $MAP_{batch-process}$	€	135, 142.5, 147, 150
Revenues per carcass for batches with prevalence > $MAP_{batch-process}$	€	105, 120, 135, 150

The benefits of a strategy are expressed in a reduction of prevalence, which is not a monetary value. To be able to rank the different strategies, the principles of cost-effectiveness (CE) of a strategy are used (Belli et al., 2001). The default strategy (D&D: both finishing and slaughtering are set to default) is the basic situation and all other strategies are compared with this situation. The relative cost-effectiveness ($RCE_{strategy}$) is the change in costs (Total costs of the strategy minus the Total costs of the default strategy ($TC_{D\&D}$)) divided by the change in average prevalence. Equation (2) expresses the calculation method:

$$RCE_{strategy} = (TC_{strategy} - TC_{D\&D})/(AveragePrevalence_{D\&D} - AveragePrevalence_{strategy}) \quad (2)$$

The $RCE_{strategy}$ provides the costs to decrease the average prevalence by 1%. A negative $RCE_{strategy}$ indicates that either the total cost of the strategy ($TC_{strategy}$) are lower than in the D&D strategy or the average prevalence of the strategy is higher than in the D&D strategy. The latter possibility does not exist, since all strategies have a reductive effect on the prevalence. Since the $RCE_{strategy}$ is calculated by comparing the chain control strategy with the default strategy, there is no $RCE_{strategy}$ calculable for the strategy D&D.

The final result is a selection and ranking of the chain control strategies with good prospects. The selection of strategies that are ranked is based on the $MAP_{longterm}$; the strategies that exceed the $MAP_{longterm}$ are not acceptable in practice. The stricter the $MAP_{longterm}$, the more chain control strategies are not acceptable. The ranking of the remaining strategies is based on the $RCE_{strategy}$.

4 Results and discussion

4.1 Detailed results of one typical scenario

As an example of the results from the epidemiological and economic model, Table 5 presents the results of a typical scenario. Equation (1) and (2) are used to calculate the $TC_{strategy}$ and the $RCE_{strategy}$. The input variables for this scenario are given below Table 5. The $MAP_{longterm}$ is not predefined; this variable does not affect the results of the epidemiological and economic model. $MAP_{longterm}$ is a variable that is used afterwards to select the viable strategies. When $MAP_{longterm}$ = 4%, all chain control strategies in the example scenario presented in Table 5 with an average prevalence above 4% are not acceptable.

Table 5 Costs, average prevalence, segmentation fractions, average revenues and cost-effectiveness of a typical scenario as an example (*Cp, Cc* and *Ct* are costs, *Bf, Bp* and *Br* are the fraction of batches per segment)

chain control strategy*	*Cp* (€)	*Cc* (€)	*Ct* (€)	*Bf* fraction	*Bp* fraction	*Br* fraction	Revenues / carcass (€)	Prev (%)	$TC_{strategy}$ (€)	$RCE_{strategy}$ (€ / %)
D&D	0.00	0.00	0.20	0.20	0.76	0.036	147.17	12.24	3.03	-
P&D	2.80	0.00	0.20	0.57	0.43	0.000	148.71	5.55	4.29	0.19
C&D	0.00	1.93	2.00	0.59	0.41	0.006	148.68	5.95	5.25	0.35
T&D	2.80	0.25	2.00	0.70	0.29	0.002	149.08	4.38	5.96	0.37
D&P	0.94	0.00	0.20	0.89	0.11	0.000	149.66	2.75	1.48	-0.16
P&P	3.74	0.00	0.20	0.99	0.01	0.000	149.96	1.29	3.98	0.09
C&P	0.94	0.00	2.00	0.98	0.02	0.000	149.93	1.25	3.01	0.18
T&P	3.74	0.34	2.00	0.99	0.01	0.000	149.97	0.97	6.12	0.27
D&C	0.00	0.60	2.00	0.78	0.21	0.010	149.23	3.65	3.37	0.04
P&C	2.80	0.60	2.00	0.83	0.17	0.001	149.48	2.34	5.92	0.29
C&C	0.00	2.02	4.00	0.77	0.23	0.001	149.28	3.30	6.74	0.42
T&C	2.80	0.69	4.00	0.87	0.14	0.000	149.60	2.04	7.89	0.48
D&T	0.94	0.17	2.00	0.93	0.07	0.000	149.79	1.75	3.32	0.03
P&T	3.74	0.03	2.00	0.99	0.01	0.000	149.96	1.17	5.81	0.25
C&T	0.94	1.98	4.00	0.98	0.02	0.000	149.94	1.10	6.98	0.36
T&T	3.74	0.24	4.00	0.99	0.01	0.000	149.98	0.90	8.00	0.44

* strategy finishing and slaughtering stage, i.e. D&D indicates that both stages follow Default strategy

($MAP_{batch\text{-}fresh}$ = 5%, $MAP_{batch\text{-}process}$ = 25%, *Rf* = € 150, *Rp* = € 147, *Rr* = € 135, serological test costs € 2 and 10% of carcasses is tested bacteriologically resulting in average costs per carcass of € 2)

The *Bf*, *Bp* and *Br* depend on the distribution of the prevalence of batches (calculated by the epidemiological model) and the $MAP_{batch\text{-}fresh}$ and $MAP_{batch\text{-}process}$. In the chain control strategy D&D, the percentage of batches with a prevalence below $MAP_{batch\text{-}fresh}$ is 20.4% (*Bf D&D)* and 3.6% (*Br D&D)* of the batches exceed the $MAP_{batch\text{-}process}$. Since the net revenues for the batches in the segment for processed-products (*Rp*) and for batches in the segment for low grade products (*Rr*) are lower than for the batches in the segment for fresh meat products (*Rf*), the average revenues per carcass are € 147.17 instead of the maximum revenues (*Rf*) of €150.00 per carcass. The revenues forgone per carcass in this chain control strategy are therefore € 2.83. There are no costs for preventive or corrective control ($Cp = Cc = 0$) and the testing costs (*Ct*) are €0.20. According to Equation 1, the $TC_{strategy}$ are € 2.83 + € 0.20 = € 3.03.

The costs ($Cp + Cc + Ct$) increase as more control measures are implemented in the chain. For strategy T&T the costs the highest (€ 7.98 = € 3.74 (*Cp*) + € 0.24 (*Cc*) + € 4.00 (*Ct*)) since the costs for preventive and corrective control are included and the testing costs for the corrective control are high. On the other hand, the average revenues per carcass for the batches that are produced in strategy D&D are lower than in strategy T&T (€ 149.98 versus € 147.17) since more batches exceed $MAP_{batch\text{-}fresh}$ and $MAP_{batch\text{-}process}$.

From Table 5, three important points can be observed. First, the $RCE_{strategy}$ of chain control strategy D&P is negative. The $TC_{strategy}$ for the chain control strategy D&P are € 1.48, which is less than the € 3.03 in the D&D strategy. The fraction of batches that exceed the $MAP_{batch\text{-}process}$ is much lower in strategy D&P than in strategy D&D, which result in higher average revenues per carcass (€ 149.66 versus € 147.17). Since the costs for the preventive control measures in the slaughtering stage are less than one Euro, the $TC_{strategy}$ for control strategy D&P are lower than for the D&D strategy. This implies that the costs per stage play a role in the selection of promising strategies. Second, most chain control strategies in which the finishing stage implements corrective measures show a high $RCE_{strategy}$. This indicates that corrective measures at the finishing stage are relatively expensive to reduce the *Salmonella* prevalence of carcasses at the end of the slaughterline. Third, there is no direct correlation between the $TC_{strategy}$ and the average prevalence. In other words, investments in control do not always result in a reduction of the average prevalence (see Figure 2).

As stated before, the $MAP_{longterm}$ determines which chain control strategies are viable strategies. In case the $MAP_{longterm}$ is defined at 4%, no chain control strategies in which the slaughtering stage follows the Default strategy is acceptable in practice since these strategies result in an average prevalence above 4%. To illustrate this, the columns

$TC_{strategy}$ and Average Prevalence of Table 5 are presented in Figure 5. With $MAP_{longterm}$ of 2%, only the last seven chain control strategies of Figure 5 fulfil the requirement of the defined acceptable prevalence level.

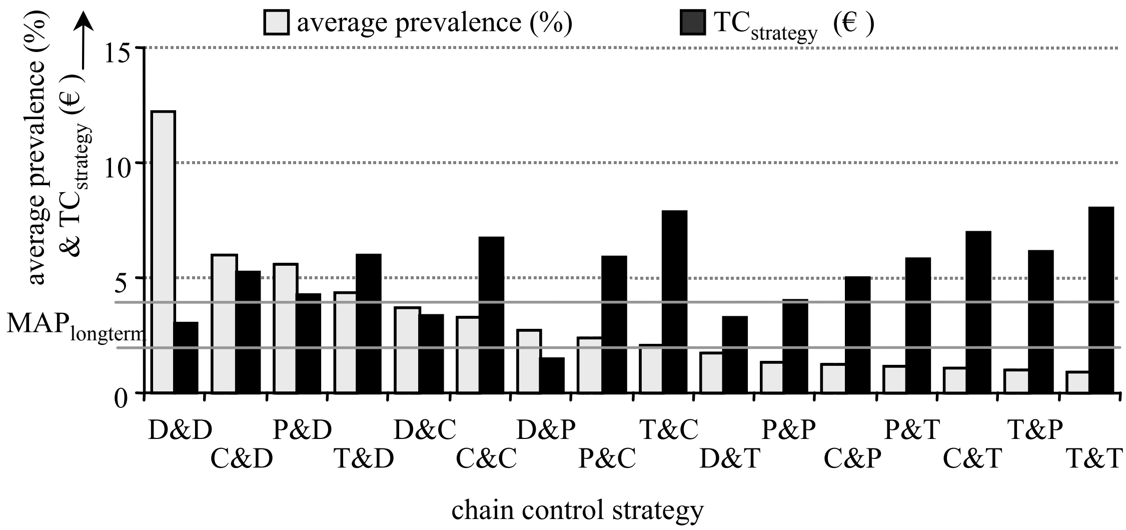

Figure 5 $TC_{strategy}$ and Average Prevalence of 16 different chain control strategies

In chain control strategies where both finishing and slaughtering implement corrective measures (C&C, C&T, T&C, T&T), the *Ct* are € 4.00 (€ 2.00 per test), which is an important part of the $TC_{strategy}$. To decrease the costs for testing, there are two possibilities: decrease the costs per test or decrease the sample size. The costs per test may decrease due to economies of scale in case the entire pork sector will offer samples to the laboratories. Beware that some some test methods may have a lower sensitivity or specificity. To measure the prevalence of a batch it is not necessary to sample all individuals per batch, the appropriate sample size can be calculated easily by epidemiological equations (Episcope, 2000). Sampling a smaller fraction of the individuals decreases the costs per individual. A reduction of testing costs results in a decrease of $TC_{strategy}$ in all chain control strategies whereas one or both stages have chosen the C- or T-strategy. For the chain control strategies with only D and P, there is no difference in loss in net returns, since these strategies do not implement corrective measures and consequently do not need a testing procedure.

4.2 Influence of MAP and revenues on the total costs

The values of $MAP_{batch\text{-}fresh}$, $MAP_{batch\text{-}process}$ and the accompanying revenues play an important role in the $TC_{strategy}$. Figure 6 presents the results for three different combinations of MAP$_{batch\text{-}fresh}$, MAP$_{batch\text{-}process}$, the other variables are equal to values used for Table 5. The Average Prevalence remains the same per strategy (no change in the epidemiological variables) in contrast to $TC_{strategy}$.

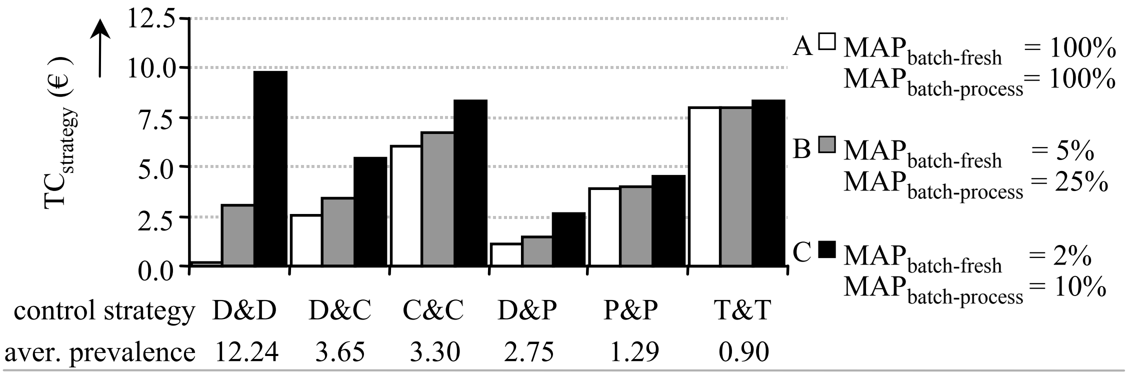

Figure 6 $TC_{strategy}$ and Average Prevalence on the long term of six chain control strategies and three different MAP$_{batch\text{-}fresh}$ and MAP$_{batch\text{-}process}$ (situation A, B and C)

Figure 6 shows that by decreasing the MAP$_{batch\text{-}fresh}$ and MAP$_{batch\text{-}process}$ (i.e. stricter targets) the $TC_{strategy}$ increases. This is expectable since more batches are exceeding the MAP's and yield reduced net revenues. In situation A, when both MAP$_{batch\text{-}fresh}$ and MAP$_{batch\text{-}process}$ are 100%, $Rf = Rp = Rr =$ € 150 and $TC_{strategy}$ presents only the additional costs. In situation B, the $TC_{strategy}$ for strategy D&D increases to € 3.03 as presented in Table 5. The effect of the revenues forgone is the largest in situation C, especially for strategy D&D where many batches exceed the MAP's and the revenues forgone are large. For the P&P and T&T strategies, the effect of stricter MAP's is limited since the numbers of batches that exceed the MAP's are limited due to better control. A small effect of stricter MAP's indicate that the fraction of batches that exceed the MAP's is low. The ranking of the six chain control strategies based on the minimum $TC_{strategy}$ depends on the MAP's. In situation A, D&D is the cheapest option and in situation B and C, D&P is the cheapest option.

The possibilities for market or authorities to regulate the prevalence of *Salmonella* in the pork chain by defining MAP's is large in case the stages in the chain did not implement control measures (e.g. D&D in Figure 6). The MAP's are effective in case the stages in the pork chain are able to implement additional control measures for further improvement of food safety. Especially, it is a regulation to reduce the number of highly contaminated batches, by increasing the penalties for these batches. Hence, not only the MAP's, but also the revenues per segment play a role. In Figure 7 the MAP$_{batch\text{-}fresh}$ and

$MAP_{batch\text{-}process}$ are 5% and 25% respectively and the *Rp* and *Rr* altered for situation D, E and F.

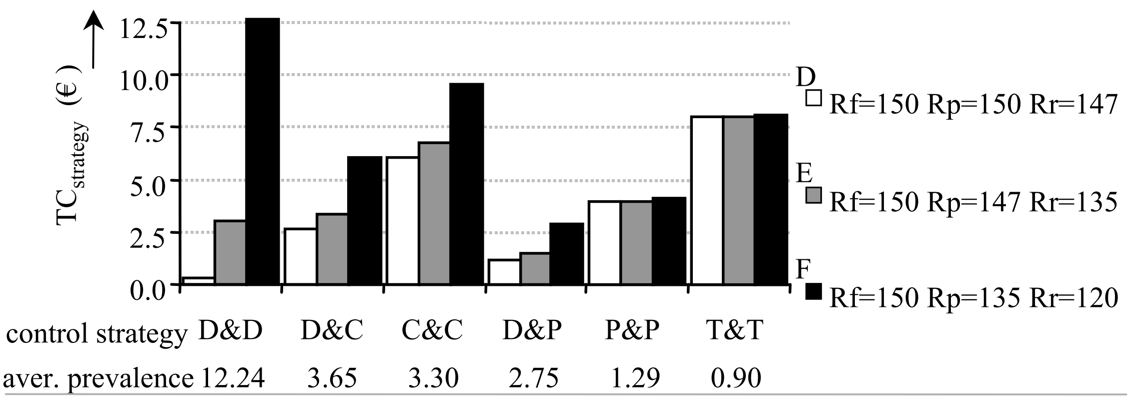

Figure 7 $TC_{strategy}$ and Average Prevalence on the long term of six chain control strategies and three different values for *Rp* and *Rr*

As Figure 6, Figure 7 indicates that decreasing the revenues for highly contaminated batches is a stimulant to choose for another control strategy in the chain in case control measures can be implemented to reduce *Salmonella*. The D&D chain strategy produces relatively many batches with a *Salmonella* prevalence above $MAP_{batch\text{-}fresh}$ and the high penalties in situation F result in large increase of $TC_{strategy}$.. Setting the MAP's and the net revenues per segment are useful tools to improve the performance of the pork chain with respect to *Salmonella*.

The principle of MAP and segmentation in revenues is product oriented. After the batches of carcasses are produced and tested, the purpose is appointed (fresh-, processed-, low-grade products). However, to maintain a good market position, the chain should be market oriented to fulfil the demands of the customer. When the product oriented principle is chosen the MAP and segmentation in revenues has to be strict to motivate the stages in the chain to fulfil the requests of the market.

4.3 Exploration of different scenarios

To get insight in the most favourable strategies based on both average prevalence and $TC_{strategy}$, 380 scenarios are executed with different combinations of the additional economic input variables as presented in Table 4. Since the epidemiological input variables are not changed, the average prevalence per strategy is equal in each scenario. The $RCE_{strategy}$ is calculated for each chain control strategy. The strategies within each scenario are ranked based on the $RCE_{strategy}$, which resulted in the ranking of 15 strategies per scenario (by definition for D&D $RCE_{strategy}$ cannot be calculated). The chain control strategy with the lowest $RCE_{strategy}$ is ranked as rank 1 and the strategy with the highest $RCE_{strategy}$ as rank 15. So, for each of the 380 scenarios, a chain control strategy received a rank between 1 and 15. Since the difference in $RCE_{strategy}$ of succeeding ranks can be very small, the 15 ranks are clustered in five categories. Rank 1, 2 and 3 are clustered in category 1, rank 4, 5 and 6 in category 2, etceteras.

Figure 8 presents the frequency per strategy in each of the five categories (n = 380 scenarios). Some strategies are in almost all scenarios in category 1, e.g. D&P and D&T and other strategies are in almost all scenarios in category 5, i.e. T&T and T&C strategy. The latter two have an unfavourable ranking because the costs are high, since especially the finishing stage often has to implement expensive corrective measures.

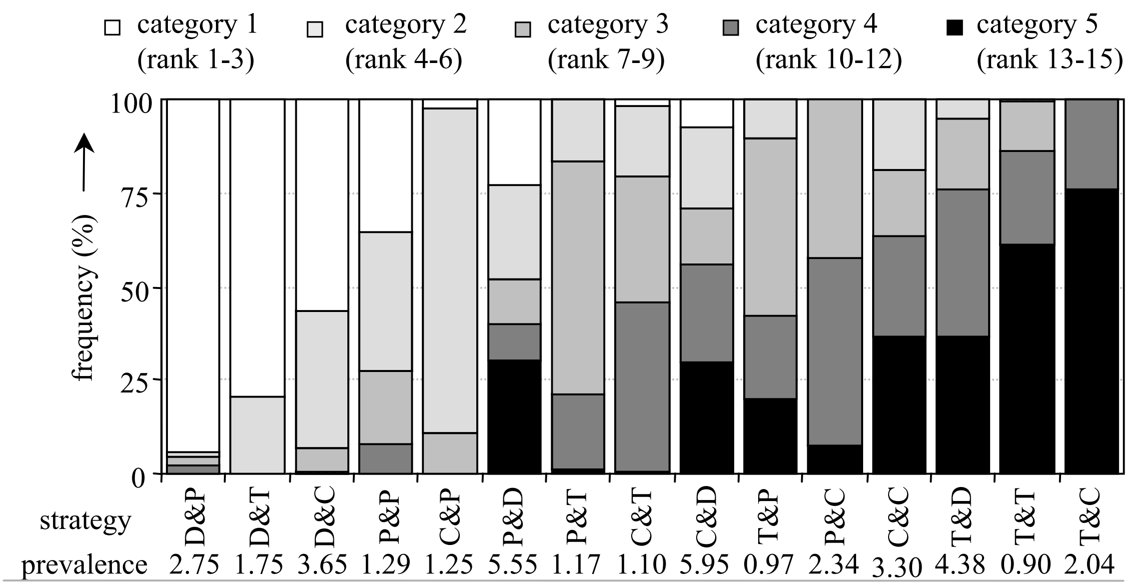

Figure 8 Frequency per chain control strategy in each of the five categories based on $RCE_{strategy}$ whereas category 1 is most favourable (n=380 different scenarios)

The $MAP_{longterm}$ determines which chain control strategies are acceptable for putting into practice. With a $MAP_{longterm}$ of 2%, strategy D&P (most favourable in Figure 8) is not an acceptable option since the average prevalence is too high. Strategy D&T is possible, although all depends on one stage which is a risk. Besides, the slaughtering stage has to implement also corrective measures, which need additional administrative organisation compared to only preventive control. The next favourable chain strategy is P&P, whereas the control costs remain the same over time without unexpected expenses for corrective control. When the costs for testing (*Ct*) decrease from € 4.00 per individual to € 0.50 per individual, the ranking of the strategies with corrective control improves due to a reduction of $TC_{strategy}$.

The ranking of some control strategies within a scenario correlates with the input values of the economic model. Increasing testing costs (*Ct*) results in a higher ranking of P&P and a lower ranking of C&C, D&T and T&T (correlation coefficient is 0.7 to 0.8). When the revenues for the segment of processed meat products (*Rp*) decreases, the ranking of T&P improves and when the *Rr* decreases, the ranking of T&D improves.

5 Conclusions

From this study, the following conclusions can be drawn:

- Determining only a low maximum acceptable prevalence for carcasses on the long term does not prevent that highly contaminated batches of carcasses find their way to the consumer.
- Segmentation of batches of carcasses based on their prevalence can be useful to increase food safety.
- Investments in control measures do not always result in a reduction of the prevalence.
- For an effective control of *Salmonella*, the slaughtering stage should implement control measures to reduce the contamination of carcasses.
- When the testing costs are high, preventive control measures are preferable to control *Salmonella* in the pork chain.
- Under the assumptions in this paper, total control (preventive and corrective) in the pork chain is not cost-effective.
- It should be noted that the paper supposed that in the default situation no control measures at all are implemented in the pork chain. However, in current practice, some farms and firms already pay attention to the reduction of the *Salmonella* prevalence.
- In general, the principle of segmentation of revenues based on MAP is a promising regulation to improve the food safety of pork with respect to *Salmonella*. For other pathogens, the same regulation system can be introduced.

Acknowledgements

The research was co-financed by Agro Chain Competence Foundation, Nutreco and Nedap Agri.

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Chapter 6

Feasibility of Salmonella control programmes: an example using the Dutch pork supply chain

Abstract

Food safety in general and, in particular, the risk of Salmonella, is of increasing interest. As pork is one of the major sources of human salmonellosis, a control programme for the pork supply chain is needed. Steps in strategic management theory provide a structured approach to design such a programme. Four steps should be taken: formulate a mission and objectives, perform an internal audit, perform an external audit, and formulate and select possible strategies. As an example, two Salmonella control programmes for the Dutch pork supply chain are designed: a Food Safety Programme and a Competitive Programme. The challenge is to design a programme that achieves the right balance between the costs of the programme and provides the best information to reduce the risk to food safety. To emphasise food safety and to prevent each country from establishing its own testing procedure, there should be a uniform testing procedure for all members of the European Union. Third countries wishing to export to the European Union should commit to these procedures.

1 Introduction

Food safety in general and, in particular, the risk of *Salmonella*, is of increasing interest. Guarantees of food safety are nowadays required not only by governments but also by domestic and international markets. As about 25% of the cases of human salmonellosis are caused by serotypes occurring in pigs, pork is regarded as a major source of human salmonellosis (Van Pelt and Valkenburgh, 2001). From 2008, it will be mandatory for all member states of the European Union to test pork and pork products for all *Salmonella* serotypes with public health significance, and to certify such products for trade (Anonymous, 2001a). To meet these statutory demands, countries will have to implement a control programme in the pork supply chain.

Among the countries already implementing such a control programme are Denmark and Norway (Nielsen et al., 2001; Sandberg et al., 2002). These programmes are still being developed and are upgraded regularly to meet the more stringent demands made by market or governments or because the *Salmonella* status in the pork supply chain has improved. Currently, representatives of the Dutch pork sector are considering the design and implementation of a *Salmonella* control programme for the pork sector. There are multiple technological possibilities to control *Salmonella* in the different stages of the supply chain. However, *Salmonella* control is a complex problem, and a structured approach is essential, to ensure that the control programme introduced is effective and efficient. The design and introduction of a control programme is a strategic decision that has to deal with all kind of uncertainties in a dynamic world. Therefore, the feasibility of a control programme in practice should be considered.

In this paper, the necessary steps for designing a feasible control programme for *Salmonella* in the pork supply chain are explored. As an example, two possible *Salmonella* control programmes for the Dutch pork supply chain are presented.

2 Concept of strategic management

In this paper the theory of strategic management is used to structure the process of setting a control programme for *Salmonella* in the Dutch pork supply chain. Strategic management is defined as formulating, implementing and evaluating cross-functional decisions that enable an organisation to achieve its objectives (David, 2001). Its underlying assumption is that organisations should continually monitor internal and external events and trends so that timely changes can be made if necessary. David's (2001) comprehensive strategic management model, presented in Figure 1, consists of the following six phases: 1) develop mission statements, 2) perform internal audit, 3) perform external audit (consists of five key forces: see section 3), 4) formulate and select strategies, 5) implement strategies and 6) evaluate performance. This paper focuses on the first four phases. The evaluation phase observes to what extent the objectives are achieved and considers adjustments in the strategy. The focus is on the design of control programmes and not on their implementation and evaluation.

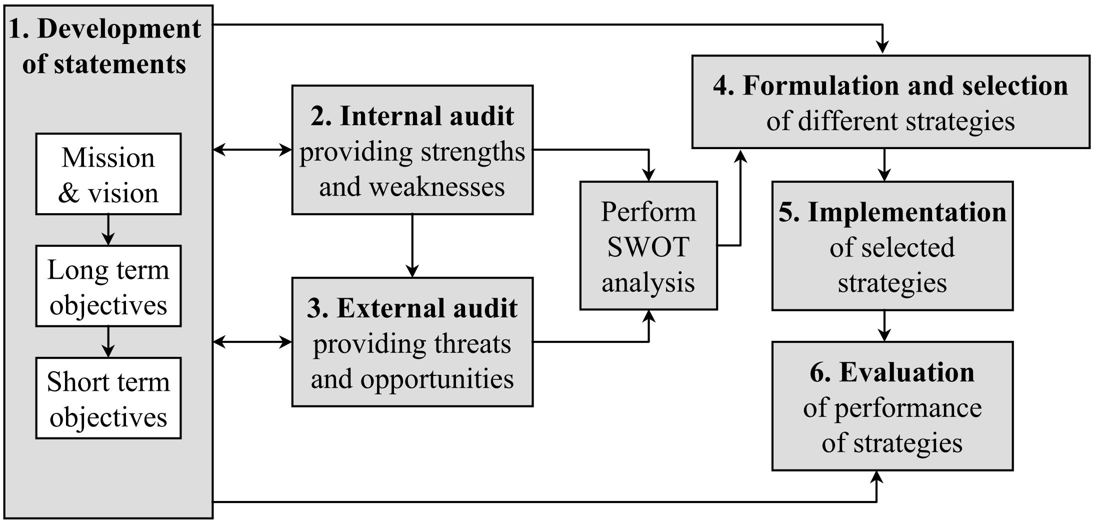

Figure 1 Comprehensive management model (David, 2001)

3 Strategic management for *Salmonella* control in the pork supply chain

As this paper uses the Dutch pork supply chain as an example, in Figure 2, the comprehensive management model has been adjusted for this chain. In this section, each step will be explained, using examples from the pork supply chain to clarify each step of strategic management. As the Netherlands will have to have *Salmonella* control in the pork supply chain in place by 2008, to comply with EU legislation, in this paper a national control programme has been assumed. The statements and objectives for the national programme are defined at country level. In the following sections, Figure 2 is discussed in detail.

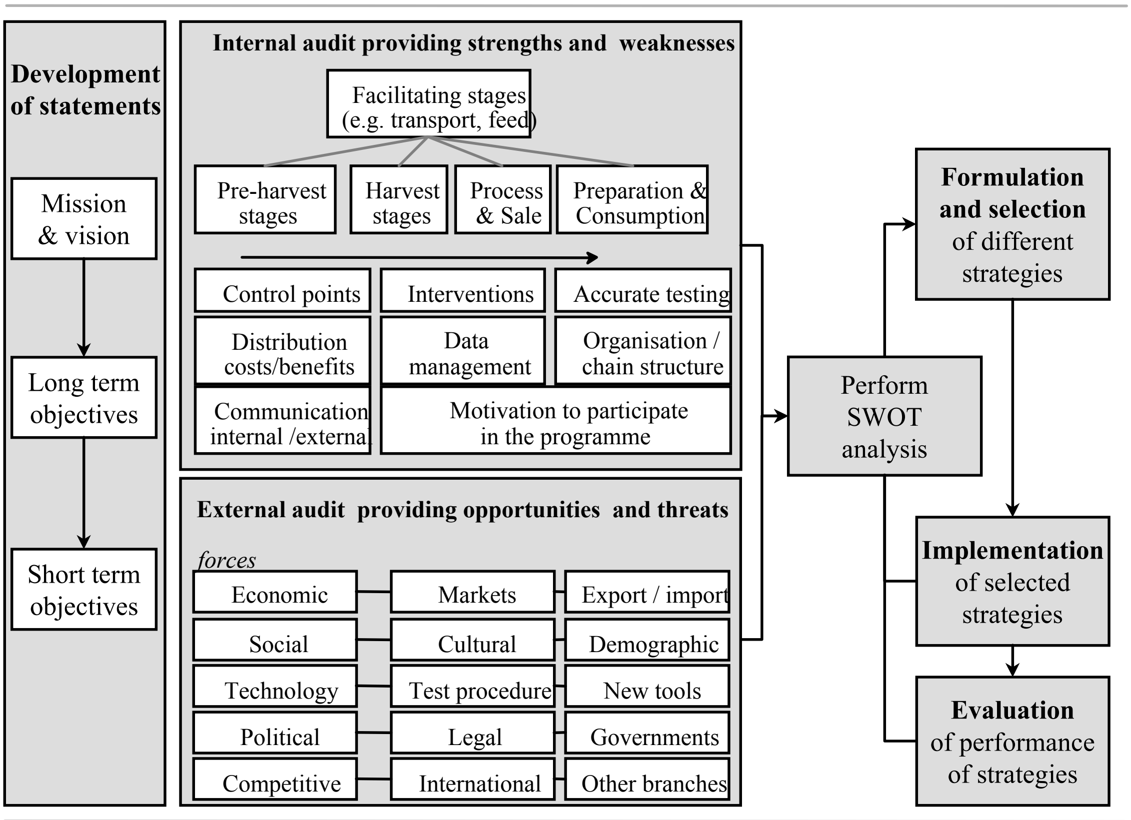

Figure 2 Strategic management model for the Dutch pork supply chain (based on David, 2001)

3.1 Development of mission statements

The first step is to define a mission and objectives. These are the basis for the continuation of the strategic management model. To define the ultimate goal, several questions have to be answered: What is the current status of the organisation? What status does the organisation want to achieve and how can it do so?

The status the organisation wants to achieve depends on the organisation's expectations regarding customers, stakeholders and competitors (David, 2001). How willing the participants in the supply chain are to cooperate in *Salmonella* control also depends on their perception of the need for such control. A mission or ultimate goal may be too abstract, or too ambitious to be reached in a reasonable timeframe. Or it may be too idealistic, e.g. to eliminate the risk of being infected with *Salmonella* (no human cases of salmonellosis caused by pork), to become the international market leader, or to protect the internal market.

The long-term and the short-term objectives must be 'SMART' (= Specific, Measurable, Achievable, Result-oriented and Time-bound) and congruent among the organisation's participants. To determine which targets in the short-term objectives are realistic and feasible, insight is needed in the current situation of *Salmonella* prevalence. Defining measurable goals makes it possible to measure the programme's effectiveness and to regularly refine and adjust the programme. Examples of direct measurable goals are: a 10% reduction of the average prevalence of *Salmonella* in one or multiple stages of the chain; a 50% reduction in the participants failing the control in one or more stages; and the eradication of a specific serotype, such as the multi-resistant *Salmonella* Typhimurium DT104. If the participants in the supply chain are to support the programme and participate fully, they have to be convinced of its advantages. To give the programme integrity, its objectives should be defined by an authoritative organisation. It is also essential to appoint a programme director with final responsibility for the programme.

3.2 External audit providing opportunities and threats

The purpose of an external audit is to make a finite list of the opportunities and threats the organisation faces. External forces can be divided into five categories: economic, social, political, technological, and competitive (David, 2001). The separate aspects per force may be an opportunity or a threat; this also depends on the country of origin and the characteristics of the organisation. The opportunities offered by the external forces and the threats to these forces can be ranked to evaluate the importance of each aspect.

Economic forces

Examples of economic forces are price fluctuations, interest rates, and export bans. The economic forces are important, since the margins in the pork sector are small and the participants have limited potential to invest in *Salmonella* control. Exploration of the present and future markets can reveal future opportunities. Exporting countries have to meet the domestic standards and also the standards of the purchasing country. It must be remembered that external forces can change unexpectedly.

Social forces

Social forces are the forces from society. A higher incidence of foodborne illness can trigger a demand for safer food. The pork supply chain cannot influence this, but should bear in mind that such demands may result in more stringent regulations stipulating the supply of safe food. The pork supply chain must deal with this in order to keep its market position.

Another aspect is the demand for differentiated products, e.g. meat from organic farming. The acceptability of measures and regulations depends on the culture and wealth of the country drawing up the regulations and of the country having to meet the regulations.

Technological forces

The technological forces include all available technological developments, such as more automated slaughter lines. These developments are opportunities to meet the objectives. The automatic testing of process or product makes better and cheaper monitoring possible. The choice of the most accurate testing procedure is described in the internal audit, but the external audit provides information about the availability of the preferred tests. Developments in ICT can result in more efficient data management and information exchange between participants in the supply chain.

Political forces

Political forces may change over time and are sometimes difficult to predict. However, some trends are clear and can be both opportunities and threats for the pork chain. The European Union has already published some stipulations for control programmes for all member states (Anonymous, 2001a). National governments also have statutory regulations that must be taken into account.

Competitive forces

To deal with competitive forces, it is essential to collect and evaluate information on competitors (e.g. Porter, 1980). When an organisation is designing a control programme for itself, it needs to take competitors' strengths and weaknesses into account. Exporting countries have to realise that their control programme has to be comparable with their competitors' programmes in the same market. The pork sector also has to keep an eye on other sectors that produce substitutes, such as beef or poultry.

3.3. Internal audit providing strengths and weaknesses

Reviewing and evaluating its internal organisation provides insight into an organisation's strengths and weaknesses. For the internal audit, the structure of the pork supply chain must be described. The main factors that should be considered in the case of *Salmonella* control in the pork supply chain are shown in Figure 2. Each pork supply chain may have other specific aspects that are strengths or weaknesses of the chain.

Definition of critical control points, interventions and standards

First, the internal processes in the pork supply chain have to be evaluated. Second, the critical control points have to be defined, which includes the location of these points and the frequency of observation of these points. Third, the possible interventions and measures have to be defined. Much research has been done on the possible interventions in each part of the pork supply chain to reduce or prevent the introduction and spread of *Salmonella* (e.g. Stege et al., 2001; Van der Gaag and Huirne, 2002). Most of the most preventive measures are based on good hygiene in the entire process.

Communication

In a control programme, it is vital to have information exchange among participants in the programme (internal communication) and to external organisations such as customers (external communication). Both types of communication have to be fitted into the internal organisation of the chain. The information needed for internal communication may be not the same as the external communication for marketing. The internal communication provides reliable information to meet clear pre-defined agreements between participants, which increases the trust between participants. In a fragmented chain structure, each individual participant will operate in an opportunistic way to ensure his or her own profit in the short-term. Opportunistic behaviour may lead to chain participants taking decisions that do not contribute to the optimal chain performance. To avoid such behaviour, reliable information exchange is important, as it strengthens the trust between chain participants. Besides exchanging information on the *Salmonella* status, the chain participants should be well informed of which interventions are most appropriate to control *Salmonella*.

In external communication, international implications play a role because the global pork producing industry is very competitive. The industry will be reluctant to use tests that are more sensitive than the tests their competitors use in other countries. From the public relations point of view it is preferable to present the problem as minor and under control (e.g. only 1% to 2% of carcasses contaminated) (Nielsen et al., 2001; Swanenburg et al., 2001). The Food Safety and Inspection Service (FSIS) of the USA have introduced a carcass swab for evaluating carcass contamination (FSIS, 2001) and Denmark has adopted the same testing procedure. Despite the poor sensitivity of this test (0.065 compared to a destructive test, (Swanenburg et al., 2003), the choice of the FSIS has set an international standard. To reach the intended goal of improvement of food safety, a more sensitive test is preferable. A possible alternative to testing and communicating the actual *Salmonella* performance in a pork supply chain is for the European Union (EU) to set its own mandatory more sensitive standard for all member states. The same test should be mandatory for third countries exporting to the EU. The selection of an accurate testing procedure is described below, under the heading "Choose appropriate testing procedures".

Data management

For a successful programme, good data management is essential and the data must be kept up to date. Hence, a reliable and skilful data manager plays a vital role in the control programme. Current data on the supplying stages are used to determine the risk of *Salmonella* being introduced to the stage that receives the supplied animals or materials (e.g. feed). As already mentioned, the communication of the results may depend on the target groups. For marketing, it is useful to classify finishing farms as is done in the Danish pork sector. For implementing new control procedures to improve food safety, such as logistic slaughter, it is necessary to have more detailed information on the prevalence of *Salmonella* on the finishing farms. To provide each participant with the accurate information, the data management should be in the hands of one single organisation. If there is one main owner of the supply chain included in the control programme, this owner is put in charge of the data management. If the chain consists of separate individuals, an independent organisation can be put in charge of the data management.

Organisation and chain structure

Due to increasing regulations and low prices, pig farming is becoming a specialist profession, and farms are becoming larger and more specialised. When several stages form one entity (integrated ownership), e.g. in large farrow-to-finish farms, the effectiveness of control and penalties increase (Bogetoft and Olesen, 2003). Instead of integrated ownership, contracts between stages may also result in a more effective programme, since both partners in the contract have agreed on the product specifications. In addition, contracting appears to represent a technological improvement over independent production, with the result that performance improves by about 20%. Note that in this calculation, contracting costs and external costs are not included (Key and McBride, 2003).

Motivation to participate

Since the need for a chain approach is clear, attention needs to be paid to motivating the separate stages and the individual participants to join the strategic plan. At each stage during the process of designing a *Salmonella* control programme, representatives from all stages of the chain should be consulted. The effectiveness of a *Salmonella* control programme is reduced if only some of the participants in a stage are actively controlling *Salmonella* (e.g. Van der Gaag et al., 2003). The programme implemented can be mandatory or voluntary. However, in both situations it will only be successful if participants are motivated. One way of motivating supply chain participants to decrease the prevalence of *Salmonella* is to use incentives (bonuses) or disincentives (price penalties). In other words, farms or firms with a higher prevalence of *Salmonella* receive a lower price for their products. Notice that in that case, the organisation imposing the price penalty has to be able and willing to do so, as otherwise, there is a risk of cheating. In Denmark, one company (the Danske Slagterier) slaughters most of the pigs in Denmark, which makes it easier to introduce price penalties. In the Netherlands, several slaughtering companies have to compete and there is a reasonable risk of evasion (not collecting the fine, or compensating for the fine) in order to keep the supplier of pigs. An alternative is for the fines to be collected by an independent organisation.

In addition, designers of the control programme have to pay attention to the *Salmonella* control regulations on the importing of carcasses slaughtered abroad.

Distribution of costs and benefits

Some stages may have to invest a lot to reduce the prevalence of *Salmonella*, and other stages may benefit from this. This issue is not of great importance if the entire chain is owned by one person or organisation, but in many cases the separate stages consist of individual (opportunistic) participants. Most control programme will yield no direct profits in the short-term. In the long term, the benefits could be an increase of production results, a better market position and fewer human cases of salmonellosis. The benefits of the latter do not flow back to the pork supply chain. Moreover, if the pork is exported, the benefits will simultaneously be exported to the importing country. However, a high-quality product posing less risk to food safety may result in higher prices or an increased market share.

In the Danish programme, the testing of live pigs and the preventive control measures at farm-level are paid for by the farmers (Nielsen et al., 2001). In Norway, the government pays for the testing costs (Sandberg et al., 2002).

Process- or product-oriented approach

The stages involved in the control programme have to be included in the monitoring. The monitoring is done to achieve the objectives of the programme, i.e. if the objective is to reduce the prevalence of contaminated carcasses, then the carcasses have to be tested. To achieve these objectives, the programme director can follow one of two approaches: process-oriented or product-oriented. A combination of these two procedures is also possible.

In the process-oriented approach, the enforcement of proper procedures for processing, construction, organisation and management of the production process is expected to lead to the intended objectives being achieved. An example of this approach is the Dutch Integrated Chain Control (IKB). IKB entails that multiple stages of the pork supply chain have to comply with specified criteria for the production and management processes. Farmers who fulfil these criteria receive a premium from the slaughterhouses. The slaughterhouses also have to meet criteria, and the certification system is an advantage in the market for pork. This type of system enables the sector to reach a minimum level of processing, which results in a better product. The IKB is flexible and is still being refined to meet new demands.

In the product-oriented approach, the product has to meet certain performance standards. These standards allow managers to tailor quality control to fit their particular farm or firm. Therefore economists often assume that achieving a given level of safety will cost less if a system with performance standards is used than if a design standard is used (Antle, 1999). For instance, the present *Salmonella* control programme of Denmark has a classification system with three categories for finishing farms (farms in category 1 have the lowest incidence of *Salmonella* and farms in category 3 the highest). Each farm is assigned to a category based on the results of serological testing (Nielsen et al., 2001). Finishing farms assigned to category 3 are fined 4% of the slaughter value, have to take faecal samples for bacteriological analysis and receive urgent advice to implement an intervention plan. The slaughterhouse has to take special hygienic precautions when pigs from farms in category 3 are slaughtered. Finishing farms infected with *Salmonella* Typhimurium DT 104 have to follow additional restrictions (Nielsen et al., 2001). Both approaches need accurate testing procedures.

Choose appropriate testing procedures

An essential part of having a successful control programme and achieving its goals is to choose appropriate testing procedures and sample sizes. In practice, there are multiple examples of inappropriate testing procedures or sample sizes that are too small given the goals. An example described by Olsson (2000) is the testing of ground beef. From each batch of 40,000 pounds, one sample is taken. If the sample is positive for *Salmonella*, the entire batch is rejected. However, for effective testing Olsson calculated that over 300 samples are necessary to be 90% confident that the batch is free of *Salmonella*. Consequently, the specification of sampling and rejecting is costly but does not noticeably increase food safety. Besides, if only the batches of ground beef are tested, the source of the contamination cannot be traced. Therefore, other critical points in the production process must also be included in the specification of sampling. In order to avoid testing procedures that are not cost-effective, the designer of the control programme should consider seven aspects (see Table 1). The internal audit has already defined the control points in the production process of the pork chain. The objectives for the short-term and the long-term constitute the basis for the accurate testing material (e.g. blood or faecal samples) and for defining the standards (e.g. which prevalence of *Salmonella* is acceptable for a specific control point). Evaluating the various test methods available (test characteristics including costs) reveals which test is most accurate. The sensitivity and specificity of the test are important characteristics. Therefore, information is needed about the types of *Salmonella* occurring in different stages of the pork chain. If new serotypes enter and establish in the population, the test must be reconsidered. The final essential step is the calculation of the number of samples needed per control point, using epidemiological equations. An insufficient sample size does not provide the information needed for an adequate control programme.

Table 1 Seven aspects for choosing an appropriate testing procedure

Aspect	Motivation	Examples
Objectives	Objectives of the programme are the basis for the programme	Eradication of *Salmonella* Typhimurium DT104 in carcasses
Information	What information is needed to meet the objectives	Information from finishing farm at herd level or at batch level
Control points	For each control point, the following steps have to be followed	The contamination of the carcass splitter in the slaughter line
Test material	The type of material tested determines the accurate test method	Faecal or blood samples to investigate the prevalence in finishing pigs
Standards	Based on the objectives, standards for the results of the test must be defined	Incidence of carcasses contaminated with *Salmonella* less than 2%.
Test methods	The test has to be appropriate for the product sampled	A test developed for *Salmonella* detection in food may be inaccurate for detecting *Salmonella* in faeces
Sample size	A proper sample size enables an adequate control programme	Epidemiological equations are available to calculate the sample size

3.4 Perform SWOT analysis

After defining the strengths and weaknesses of the internal organisation and the opportunities and threats originating from the external world, a SWOT matrix is constructed (see Table 2) (David, 2001). After the external and internal audits have been performed, the key opportunities, threats, strengths and weaknesses are selected. These key aspects from the internal and external audits are presented in the matrix. This SWOT matrix is a helpful tool for designing control strategies.

Table 2 SWOT matrix

	S (strengths) - List of strengths	**W** (weaknesses) - List of weaknesses
O (opportunities) - List of opportunities	SO strategies: use strengths to take advantage of opportunities	WO strategies: overcome weaknesses by taking advantage of opportunities
T (threats) - *List of threats*	ST strategies: use strengths to avoid threats	WT strategies: minimise weaknesses and avoid threats

3.5 Formulation of different strategies

The SWOT matrix and the long- and short-term objectives are the basis for designing strategies or *Salmonella* control programmes. So, after the SWOT analyses, decisions are made about the design and implementation of the control programme.

4 Feasible strategies for Dutch pork chain

Like all member states of the European Union, the Netherlands has to develop a *Salmonella* control programme for the pork supply chain. Since the basic end-product of the pork chain is a chilled carcass, the focus of the strategy or programme is on the stages from breeding through slaughtering, including the facilitating stages. In this section, two different programmes are briefly worked out, following the phases of the strategic management concept. Sometimes, the different phases overlap or interact.

4.1 Salmonellosis in the Netherlands

The Dutch pork chain has a self-sufficiency rate of 259% . Over 3 million piglets and almost 1.5 million finishing pigs are exported annually (Anonymous, 2001b). Hence, the international market is very important for the Dutch pork sector and the Dutch *Salmonella* control programme of the pork chain must be able to compete with other countries on the international market. In the Netherlands, the annual number of cases of human salmonellosis is estimated at 3 per 1,000 inhabitants (van den Brandhof et al., 2003). About 25% of the human cases are caused by serotypes occurring in pigs (Van Pelt and Valkenburgh, 2001). The estimated current average prevalence of *Salmonella* in the entire finishing pig population in the Netherlands is 25%. *Salmonella* is present in about 90% of all Dutch pig farms (serological testing for antibodies at cut-off %OD>10) (van der Wolf et al., 2001).

4.2 Stages included in or excluded from the programme

The stages included in this section are breeding, multiplying, finishing and slaughtering. The stages transport and feed manufacturers have been excluded because in the Netherlands these stages already have strict regulations to avoid contamination or cross-contamination with *Salmonella.* In response to several outbreaks of infectious animal diseases in the last ten years, the national regulations for transportation of farm animals have been tightened. Furthermore, the transport sector and the feed manufacturers have implemented their own quality assurance programme incorporating the Good

Manufacturing Practice (GMP) code (Anonymous, 2002; Anonymous, 2003). Hence, the Dutch transportation companies are considered to be minimising cross-contamination between batches of pigs sufficiently, and there is thought to be a very low risk of *Salmonella* being introduced by pelleted feed.

4.3 Objectives of two control programmes

We had designed two different hypothetical programmes: the food safety programme (FSP) and the competitive programme (CP). The first programme has been drawn up from the perspective of food safety, whereas the second is based on the perspective of retaining a competitive market position.

The ultimate goal of the FSP is to prevent all human salmonellosis caused by pork products. Since there are about 50,000 cases per year and 25% are attributable to serotypes occurring in pigs, about 12,500 cases may be caused directly or indirectly by pork. The long-term measurable objective is to reduce this number by 50% in three years. The short-term objective is to reduce the carcass contamination to 10% contaminated carcasses in 2004. This percentage can then be reduced by 1% each subsequent year, until a zero level is reached in 10 years' time.

The ultimate goal of the CP is to ensure the Netherlands becomes the market leader in the international market with respect to *Salmonella* control. The long-term objective is to be able to follow the current market leaders, and the short-term objective is to design a programme that is comparable with the programme of the Netherlands' major competitors. Since Denmark is the major competitor in the international market for high-grade products, the CP must be at least as good as the Danish programme.

Both programmes must include a prevention strategy for the entire chain. For each participant in the pork chain, a whole set of possible prevention measures and interventions is known (e.g. Stege et al., 2001). These measures are identical for both programmes and will not be discussed in further detail. Only the steps the pork chain should consider while designing two different control programmes are described in this paper.

4.4 SWOT analysis for Dutch pork chain

One SWOT analysis was performed for both programmes. Several aspects can be concomitantly an opportunity and a threat, depending on one's point of view, so the distribution of the aspects is debatable. Besides, it is impossible to cover all aspects, so recent developments must be evaluated regularly, in order to keep the SWOT up to date.

The same is applicable to the strengths and weaknesses from the internal audit. The results from the external and internal audit are presented in Table 3. The inner part of SWOT matrix as presented in Table 2 provided possible strategies using the opportunities, threats, strengths and weaknesses. These strategies for the *Salmonella* control programme are presented in Table 4.

Table 3 Internal and external audits for Dutch pork chain related to *Salmonella* control

Internal audit	External audit
Strengths	*Opportunities*
S1: Familiar with quality systems such as IKB S2: Advanced quality system of feed manufacturers S3: Strict regulation of the transport of pigs and pork S4: Knowledge about possibilities of *Salmonella* control in regular pork production S5: Most chain participants are professional and skilled S6: Increase of use of computer and internet S7: Experience and implementation of identification and registration in the chain S8: Developments and possibilities for tracking and tracing S9: Strong international market position based on quality and quantity	O1: Differentiation of pork market O2: Consumer concerns about food safety O3: Increase in demand for ready-to-eat products (high value and options for decontamination) O4: Developments in slaughter techniques O5: Developments in data management and ICT O6: Developments in test methods O7: International experience in *Salmonella* control O8: Limitation of duration of transport of live animals (slaughtering in the Netherlands gives extra value to the Dutch pork sector) O9: In good time to anticipate on EU legislation

Table 3 continued

Weaknesses	*Threats*
W1: Distrust between chain participants W2: Opportunistic behaviour of chain participants (note: W1 & W2 are related) W3: Fragmented chain structure W4: Small profit margins result in limited capital for investments W5 Individual participants not fully aware of their contribution to risks to food safety W6: Limited information exchange between stages W7: Lack of knowledge about *Salmonella* control in alternative production systems such as organic W8: Limited influence and co-operation of stages from breeding through slaughtering with final stages in the chain W9: Disproportionate distribution of costs and benefits W10: Risk of fraud	T1: Differentiation of pork market T2: International price for pigs and pork T3: Export bans T4: High production costs due to high labour costs and scarcity of farm land T5: Increase of susceptible human population T6: Limitation of duration of transport of live animals (threat to Dutch export position) T7: National regulation in the short term T8: Developments in other branches that produce substitutes for pork T9: Competition on international market

Table 4 SWOT strategies for Dutch pork chain related to *Salmonella* control

Strategies related to strengths and opportunities	*Strategies related to weaknesses and opportunities*
SO1: implement new Salmonella programme in current quality systems (S2, S3, S7, O5, O9) SO2: communicate improved food safety by a certification or labelling system (S7, S8, O2) SO3: make use of new test methods and the possibilities to communicate the results automatically (S6, O6) SO4: co-operate with research and companies that manufacture inventory and equipment for the pork chain (S4, O4, O6, O7) SO5: make use of the current market position to promote the Salmonella programme (S9, O2, O3)	WO1: make use of interest in food safety and new food patterns to get access to markets for high-grade products and receive higher prices (W4, W10, O1, O2, O3) WO2: improve the information exchange between stages (W1, W5, O5) WO3: stimulate vertical collaboration or integration (W1, W2, W3, O7) WO4: export pork products with added value instead of exporting live finishing pigs (W4, W10, O8)

Table 4 continued

Strategies related to strengths and threats	*Strategies related to weaknesses and threats*
ST1: Include entire chain in the control programme to be able to implement a programme that is most cost-effective for the entire chain (S1, S4, T2) ST2: use and improve the current identification and registration and the current tracking and tracing to serve differentiated markets (S6, S7, S8, T1, T8) ST3: exploit possibilities in Dutch system to implement parts of the competitors system (S1, S2, S3, T9)	WT1: consider possible deficiencies in the programme to reduce the risk of fraud (W1, W2, T3, T8) WT2: improve knowledge about Salmonella control in different production systems (W7, T1, T7) WT3: improve information exchange about the responsibility of individual producers and about the need to control Salmonella (W5, W6, W8, T2) WT4: increase automation in slaughter process (reducing personnel costs, but very high investment costs) (W4, T4)

4.5 Food Safety Programme

As already stated, the ultimate goal of the FSP is to prevent all human salmonellosis caused by pork products. The long-term measurable objective is to reduce this number by 50% in three years, and the short-term objective is to reduce the carcass contamination to 10% contaminated carcasses in 2004. This percentage can then be reduced by 1% each subsequent year, achieving zero level in 10 years' time. To test each individual carcass is too costly and not necessary, so, instead, batches of carcasses can be tested. A batch can consist of a fixed number of carcasses, i.e. 100 or 1000, or the entire production of one day. Batches yielding too many positive samples need additional care (decontamination of carcasses or further processing to eliminate the contamination). Hence, the monitoring is intense and the results per test indicate whether the batch is appropriate for sale as fresh pork products. To ensure that an accurate picture of the level of contamination is formed, a sensitive test must be used. The most accurate test is a destructive test or an extended carcass swab of 1400 cm2 (Swanenburg et al., 2000). The best time to sample the carcasses is just before chilling and cooling (Swanenburg, personal communication).

If a batch is defined as a group of 1000 carcasses, the sample size can be calculated. For example, in a thousand carcasses, if there is a contamination level of 10%, and the confidence level is to be 95%, 29 samples need to be taken (Win Episcope, 2000). All these samples need to be negative if one is to infer that the prevalence is less than 10 %. Assuming that the costs per test for such quantities are about € 15 and that of the 18 million pigs slaughtered per year 2.9% are sampled, the total costs will be almost € 8 million for the bacteriological testing in the first year. To prove a prevalence level below 1%, over 25% of the animals must be tested, resulting in testing costs totalling over € 45 million. Furthermore, the costs of the additional measures if the prevalence exceeds a predefined maximum acceptable prevalence have to be included.

To reduce the risk of positive carcass samples, the status of the pigs entering the slaughterhouse should also be known. Infected or contaminated groups of pigs must be handled with special care. Pigs that carry *Salmonella* bacteria in the intestines and shed or excrete *Salmonella* form the highest risk for carcass contamination in the slaughterline. Therefore, the FSP includes bacterial testing of each batch destined for the slaughterhouse. The best method is to pool the samples (faeces of 5 to 10 pigs per sample), since infected pigs do shed bacteria intermittently (Gray et al., 1996; Hendriksen et al., 2002). Positive batches should be handled with additional care during transport, at the lairage and during slaughtering. To reduce costs, the farmer can take these samples. The cost of analysing the samples if 18 million pigs are slaughtered per year, given an average batch of 75 pigs, one sample per batch and € 15 per sample, is € 3.6 million. It is not recommended to take blood samples from live pigs at the end of the finishing, since the risk of the pigs dying prematurely due to the stress caused by the sampling increases as the finishing period progresses. Besides, the costs of serologically sampling each batch before slaughter are very high. Batches of pigs found to be positive should be transported and slaughtered with additional hygiene measures, to reduce the risk of carcass contamination. Note that if the farmer risks severe repercussions if the sample is positive, there is a greater risk of fraud in the sampling (*WT1* from Table 4). There are techniques to reduce this risk, such as additional testing on artificial ingredients in the sample (*SO3* from Table 4). The additional costs of the special care during transport and slaughtering must also be included.

Earlier stages in the pork production chain, i.e. suppliers of breeding / multiplying gilts, and growers, should also determine their *Salmonella* status, either from blood samples (from gilts) or from faecal samples (from growing pigs). This would enable the farms that receive these pigs to implement control measures in an early stage of production.

The FSP can be implemented in the current quality system (*SO1*); this reduces the implementation costs. The costs for testing are high and must be recouped from higher prices or increase of market share, i.e. by labelling the pork (*SO2*). Alternatively, a third party, e.g. the government, can pay these costs. To ensure that all stages will take action to prevent the introduction and spread of *Salmonella*, the system can be mandatory, or the prices should depend on the *Salmonella* status of the product the chain participant produces (*WO3*). Participants who do not join the programme can be penalised the most heavily. A public announcement of how each participant in the chain has performed with respect to *Salmonella* is also a way of motivating participants to reduce the prevalence of *Salmonella* (*WT3*). A chain participant can easily introduce *Salmonella* by buying sows, piglets or pigs, which is why public communication of the performance of stages is useful (*SO3*, *WO2*). Notice that in the FSP, all pigs for consumption have to be tested — including sows.

The total costs of the programme—including the testing costs, costs of additional measures and interventions if batches test positive—are high, as is the cost of the system of data management. The FSP is a very expensive programme and unless subsidised would probably not be feasible to introduce. The returns from the initial investments are not immediately visible. In the long-term the need for subsidies will decrease when the pork chain achieves a better market position and higher prices for the safer product. However, these aspects need time.

4.6 The Competitive Programme

The Competitive Programme aims at to be comparable with the programme of major competitors and, in the long term, to overtake competitors. Denmark is one of the Netherlands' major competitors in the pork supply chain. It has had a *Salmonella* control programme since 1995 (Nielsen et al., 2001). The Dutch pork chain could copy the main aspects of the programme (*ST3*) and in the short term will have to achieve the prevalence results that are as good as, or better, than those of the Danish pork sector. The two major aspects of the Danish programme are the categorising of finishing herds and the measuring of the prevalence of contaminated carcasses. All finishing farms that produce over 200 finishing pigs per year are included in the Danish monitoring programme. This monitoring programme entails taking meat drip samples monthly from pigs from each finishing herd, for serological testing. Depending on the herd size of the farm, 60, 75 or 100 samples of meat drip are taken per year per farm. A sample is tested with the Danish MIX-ELISA test; the cut-off OD % is 20. Based on the results of the samples per three months, a farm is assigned to one of three levels. Level 1 indicates that the average prevalence is less than 40%, level 2 indicates the prevalence is estimated as being between 40 and 70%, and level 3 indicates a prevalence exceeding 70% (Nielsen et al. 2001). Around 3.3% of Danish finishing farms are assigned to level 2 and 1.6% to level 3. For the Dutch situation with 14,000 farms with finishing herds and an average of 70 samples per farm (€ 2 each), the annual testing costs are almost €2 million. The other major aspect, the prevalence of contaminated carcasses per year, is measured in Denmark by swabbing 5 carcasses per day after cooling with a 100 cm^2 swab of the sternum, hind leg and jowl respectively (Nielsen et al., 2001).

For the CP standards for the following aspects, the following have to be defined for the serological sampling: a testing procedure, a cut-off OD % and the limits for the three levels that are used for assigning finishing farms. Since competition is the leading force, the results of the CP in the Dutch situation should not exceed the prevalence levels of the Danish programme. A logical first step is to monitor the current prevalence on the finishing farms, using the same testing procedures as the Danes do. If the Dutch situation is equal to or better than the Danish one, the same standards can be used. If the results are better, it is useful to apply the CP standards in a marketing strategy (*WO4*). If the Dutch situation appears to be worse than the Danish situation, there are two options. The first is to admit that the prevalence of *Salmonella* in the Dutch pork supply chain is higher than the prevalence in the pork supply chain of the major competitors (*SO5*). Then, to be able to operate on the international market *(ST1)* it is essential for there to be communication about the planned control strategies that will improve the Dutch *Salmonella* situation in the pork supply chain. Although this strategy is straightforward, it might be risky from the marketing point of view. The second option is to use adjusted standards for the sampling, and to stress the communication on the final results, i.e. percentage of farms in levels 1, 2 and 3 (*SO3*). Meanwhile, the Dutch pork supply chain will have to reduce the prevalence of *Salmonella* in order to be able to catch up its competitors. However, the competitors may emphasise the differences in sampling standards and use that as an advantage in their own marketing. Neither of these options leads to the achievement of the short-term objective.

4.7 Additional aspects for both Programmes

To reduce the prevalence of *Salmonella* in live animals and carcasses, each participant in the chain has to realise the importance of a chain approach and the vital need for stages in the chain to exchange information about performance with respect to *Salmonella* (*WO2, WT3*). If there is motivation to invest in the performance of the final product of the chain, chain participants will focus on their farm or firm, especially if the chain is fragmented—as it is in the Netherlands. Ways of reducing such opportunistic behaviour include information exchange, financial incentives, integration of stages, or vertical co-operation (*WO3*). In the Dutch pork chain, additional attention is also given to alternative systems of pig farming; for example, the Dutch government is striving to increase of organic farming (*WT2*).

<u>Considering both programmes</u>

The main choices that both programmes offer are shown in Table 5.

Table 5 Major choices offered by the Food Safety Programme and the Competitive Programme

	Food Safety Programme	Competitive Programme
Ultimate goal	Elimination of human salmonellosis caused by pork.	Becoming market leader in the international pork market.
Long-term objectives	50% reduction of human salmonellosis caused by pork in 3 to 5 years.	Being able to follow the major competitors in terms of the assurance of *Salmonella* control
Short-term objectives	Batches of carcasses with contamination above the threshold level will have to be decontaminated or processed (confidence level of 95%).	1) less than 2% of the finishing farms have a herd prevalence above 70% (Nielsen et al. 2001) 2) the prevalence of contaminated carcasses is below 2% per year
Information needed	Whether batches of carcasses are contaminated with *Salmonella* above the threshold level.	1) categories of prevalence levels of finishing herds 2) prevalence of contaminated carcasses per year
Control points	1) herd level: *Salmonella* status at herd level from all farms with pigs for consumption 2) carcass level: *Salmonella* status of batches of carcasses	1) herd level: categorising herds with respect to *Salmonella* 2) carcass level: prevalence of carcasses contaminated with *Salmonella*
Test material	1) herd level: faecal samples per batch delivered 2) carcass level: meat cuts or swabs per batch slaughtered before cooling	1) herd level: blood samples on farm or at slaughterhouse 2) carcass level: swabs of carcasses after chilling
Standards	1) herd level: batches with positive samples need additional care* 2) carcass level: batches with positive samples need additional care*	1) making categories so that results are comparable with major competitors 2) less than 2% contaminated carcasses per year

Table 5 continued

Test methods	1) herd level: Faecal samples: pooled samples per batch delivered tested in a bacteriological test with pre-enrichment steps (Baggesen et al., 1996) 2) carcass level: destructive method or large swabs of 1400 cm^2 per carcass (Swanenburg et al., 2000)	1) herd level: Blood samples: *Salmonella* mix-ELISA for detection of antibodies (Nielsen et al., 1995) 2) carcass level: small swabs of 3 times 100 cm^2 per carcass (Swanenburg et al., 2003)
Sample size	1) to detect 1 shedder in 80 pigs 76 samples should be taken; to detect 8 shedders 24 samples should be taken (CL 95%) (Win Episcope, 2000) 2), to detect a prevalence of 10% 29 samples should be taken; to detect 1% 258 samples should be taken (CL 95%) (Win Episcope, 2000).	1) 60 to 100 meat drip samples per finishing farm per year 2) one pooled sample of 5 carcass swabs per day (Nielsen et al. 2001)

As already mentioned, both programmes should include a prevention strategy. The FSP is an extended and expensive programme that is not practicable. The CP is cheaper and more feasible, although it is based on the programme of another country and therefore the strengths of the Dutch pork supply chain and the opportunities in the Netherlands may be not fully exploited. However, since the margins in the pork sector are limited, the willingness to invest in a solid food safety programme are limited, as are the possibilities of doing so. The large sample size in the FSP is a costly aspect that can be reduced by introducing a sample size based on performance; for example, the prevalence of contaminated carcasses at a slaughterhouse should be below 1.5% per year. If this prevalence is exceeded, the slaughterhouse has to report the prevalence per quarter until the target of 1.5% is reached again. Hence the testing costs in the FSP can be considerably higher. In both programmes, the data management entails processing large databases and providing correct information to each chain participant.

5 Discussion

The formulation of the ultimate goal and of the long- and short-term objectives is essential for the design of the control programme. In practice, the formulation of these objectives often does not receive enough attention. Sometimes the programme itself seems to be the ultimate goal. When such a programme is implemented, it may be more complicated and expensive to carry out changes in the programme, due to new insights. This paper has focussed on the first four steps of strategic management. However, the implementation and evaluation need just as much attention. A good design will fall apart if the implementation is not carried out in a well thought-out manner. Therefore, several practical steps have to be taken, such as the organisation of logistics of test materials and the appointing of the people responsible for the programme. These aspects have not been included here, since they are part of the organisation of the implementation.

The programme should be evaluated regularly, i.e. every two years. In the evaluation, not only the actual programme should be considered, but also the objectives and the SWOT matrix.

The main reason for designing a *Salmonella* control programme in the pork chain is to improve food safety. However, it is not possible (yet) to eliminate *Salmonella* in the entire pork supply chain, since *Salmonella* is ubiquitous and is present in each stage of the Dutch pork chain. Although the Food Safety Programme may result in the lowest prevalence of contaminated carcasses, its high costs make it unfeasible to implement. The risk of a programme such as the Competitive Programme is that the food safety aspect is pushed into the background. Furthermore, a good programme from a competitor may lose its effect to improve food safety when copied by another country, because of differences between the two countries' structure and organisation. For example, if slaughter companies are competing for business and they have to fine finishing farms with a high prevalence of *Salmonella*, there is a higher risk that they will repay the fines, in order to keep the finishing farms as suppliers.

In the programmes described in this paper, the feed manufacturers and transport companies have been ignored. In other countries, these stages may play an important role in the spread of *Salmonella*, and so it is essential for the control programme to devote special attention to these stages.

6 Conclusions

The concept of strategic management offers a structured model to design a *Salmonella* control programme. Each step has to be carried out carefully. The ideal control programme does not exist, since interests may differ. From the consumer's point of view, the control programme must be very effective but without a large increase in the price of pork. Form the point of view of the stages up to harvest, the margins to invest in food safety are small, and advantages such as higher prices or increased market share are essential but cannot be relied upon.

From the point of view of competitiveness, it is tempting to opt for a testing procedure that results in a low prevalence. However, to emphasise food safety and to prevent each country from establishing its own testing procedure, thereby making inter-country comparisons of results impossible, there should be a uniform testing procedure for all members of the European Union. Third countries wishing to export to the European Union should commit to these procedures.

Sensitive testing procedures are not necessarily more expensive than less sensitive procedures. However, from the marketing point of view it may be more attractive to test with less sensitive tests, since the prevalence found may be lower.

The challenge is to design a programme that achieves the right balance between the costs of the programme and provides the best information to reduce the risk to food safety.

Acknowledgements

This study was in part financed by Agro Chain Competence, Rosmalen, The Netherlands. We thank Christien Ondersteijn for her useful help and comments with respect to the Strategic Management theory.

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Chapter 7

General Discussion

1 Introduction

Pork is a popular meat and it is produced under a wide variety of production systems ranging from simple backyard pigs to large-scale integrated pig industries with sophisticated measures. This thesis has dealt mainly with the conventional pork supply chain in the Netherlands. The main objective of this research was to gain insight into the epidemiological and economic effects of different strategies to improve the food safety of pork with respect to *Salmonella*. Insight has been gained into the effects of measures and interventions in the pork chain on the prevalence of *Salmonella* in the end product. This insight can support decision making to improve food safety. The core activity of the thesis has been to design and use two simulation models, one to obtain insight into the epidemiological aspects of *Salmonella* control and one to obtain insight into the economic effects of *Salmonella* control. The requirements of simulating a system can be summarised in four steps (Dijkhuizen and Morris, 1997; Banks, 1998): 1) define the system and formulate the problems and objectives, 2) collect data relevant to the model and construct the model, 3) verify and validate the model, including a sensitivity analysis and 4) produce runs and analyse the results.

The first step, definition of the system and the objectives forms the basis of the following steps and is presented in Chapter 1. In short the topics of the chapters are mentioned: Chapter 2 presents a survey among experts in Denmark and the Netherlands, to determine the main control measures in each stage of the pork supply chain and insight into the infection dynamics of *Salmonella*. Chapter 3 describes of the epidemiological simulation model. Chapter 4 presents the economic model and the cost-effectiveness of implementing control measures in one or several stages. Chapter 5 presents a system to distinguish revenues for batches of carcasses based on their prevalence. And Chapter 6 presents the principles of strategic management to define the aspects that are important for the design and implementation of a *Salmonella* control programme in a pork supply chain.

This General Discussion is focused on the research approach (section 2.1), data collection (section 2.2), model design (section 2.3), verification and validation (section 2.4), results (section 2.5), brings in the issue of costs and benefits (paragraph 3). It also gives an example of practical implications of the results of this thesis (paragraph 4) and presents the main conclusions of the thesis (paragraph 5).

2 Research approach

The first step of simulation is to define the objective and the system. The main objective has been mentioned before and focuses on the food safety of pork. The system of interest in the research focuses on the stages of the pork supply chain through to the chilled carcass, since this forms the basis of all pork products. The system that has been studied contains five stages of the pork supply chain i.e. multiplying, finishing, transport, lairage and slaughtering. Facilitating stages such as feed manufacturers, veterinarians and service companies have been included indirectly. For instance, the introduction of *Salmonella* by feed products is included in the model, but the implications for the feed manufacturers are excluded. The stages after the slaughtering stage have not been included. Breeding, the stage before multiplying, is excluded since it appeared from the literature that the effect of breeding herds on the final *Salmonella* prevalence of finishing pigs and carcasses is very limited (Berends et al., 1996). After chilling, the carcass is cut into parts and exposed to different types of processing.

2.1 Selection of a modelling approach

To gain insight into the epidemiological and economic effects of different strategies to improve the food safety of pork with respect to *Salmonella* two approaches are possible: performing field studies and computer modelling (Figure 1). Each approach has its own strengths, weaknesses and requirements. Strengths of field research are that all actual influences are included in the experiment and that it provides real-life data. Weaknesses of field research are that the research is very expensive, time-consuming, it is always retrospective and only a limited number of strategies can be tested (Banks, 1998). Besides, sometimes field research is impossible since it can be disruptive, i.e. infecting a pig population with a highly contagious disease or because of ethical objections (Dijkhuizen and Morris, 1997). A modelling approach can be a mathematical model or a physical model. A physical model is a scale model of the actual system (Law and Kelton, 2000) such as a model of a building to evaluate the effect of the building design on local air movement. With respect to the spread of pathogens in supply chains, this approach is not possible. Mathematical models represent a system in terms of logical and quantitative relationships that can be changed to see how the model reacts, and thus how the actual system would react – if the model is valid (Law and Kelton, 2000). There are two approaches for the mathematical model (Figure 1): analytical solution and simulation. Law and Kelton (2000) state that analytical solutions are preferable, however when mathematical models are highly complex, simulation is often the only possibility. Simulation models can be stochastic which means that uncertainty is included or deterministic.

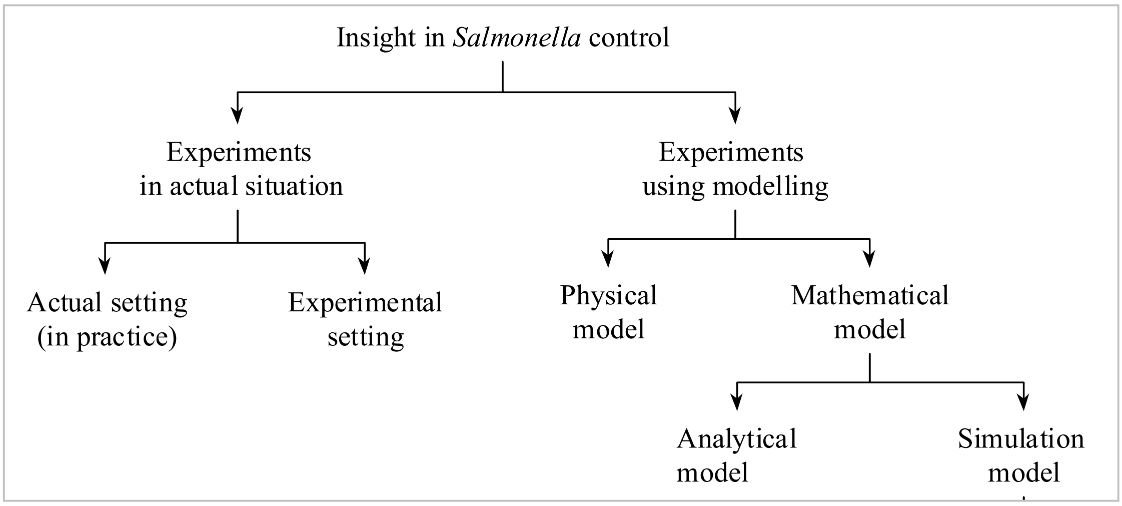

Figure 1 Ways to study a system (based on Law and Kelton, 2000).

Knowledge about the interaction and relations between the epidemiological and economic aspects of the system was limited. Therefore, two separate models were designed, one for the epidemiological aspects and one for the economic aspects of *Salmonella* control in the pork supply chain. The results of both models have been combined in order to calculate the cost-effectiveness of control in the chain. For both models the simulation modelling approach has been chosen. The epidemiological model is stochastic to make it possible to include the natural variation in the introduction and spread of *Salmonella* in the pork chain. The economic model is deterministic. By means of a simulation model, it is possible to study the effect of multiple *Salmonella* control strategies. It is also possible to study prospective strategies that do not yet exist in practice, such as new testing methods or measures. Other strengths are the possibility of setting priorities for further research, especially in the case that practical research is still limited. Besides, it can be helpful to get insight into processes that are not totally clear yet.

2.2 Data collection

The second step in simulation modelling consists of two elements, data collection and constructing the model. In this paragraph data collection is discussed. For the epidemiological model data on the introduction and spread of *Salmonella* in the pork chain and on the possibilities of preventing or reducing this introduction and spread were required. The topic of microbial food safety is a delicate matter. Private companies such as slaughterhouses and Research and Development departments of large industrial firms are reluctant to make information public. Besides, the large competition in the pork chain limits openness. This lack of (accessible) data has complicated the design of the epidemiological model. Although the interest in microbial food safety is enormous, qualitative and quantitative data on microbial dynamics in several stages of supply chains are limited. Most research described in literature provides data of experimental settings, whereas pigs in a single stage were orally infected once with a high dose of *Salmonella*. The results of these experiments may not be directly applicable for the situation in the field, however they give insight in the infection dynamics. Reduction effects of specific control measures in the chain on the infection dynamics were not known exactly. For instance, it is known that the use of fermented feed reduces the *Salmonella* prevalence in a group of pigs, but it is not clear which epidemiological parameters are influenced. Possible parameters are the duration of the infectious period and the carrier period, the number of bacteria per gram faeces or the infection rate. These aspects are of interest for future experimental research.

When the available data are limited, expert elicitation is a proper method to collect the best information available today (Horst, 1998). The degree of expertise of the respondents is a crucial factor that can be measured by including 'test questions' of which the answers are known beforehand. To increase the number of respondents, experts from several countries can be consulted as was done in the research described in this thesis (Chapter 2). However, it is not recommendable to include experts from all over the world to estimate variables that are specific for a certain pork production system or chain organisation, since they refer to different concepts and definitions. In-depth interviews that could solve this problem are very time-consuming. An additional advantage of consulting experts is that not only the published knowledge becomes available, but also research information that is unpublished.

Bahnson (2001) presented the limited availability of literature on *Salmonella* control in the chain and the economic aspects. From his literature survey, Bahnson (2001) concluded that research on the interaction of the biology, *Salmonella* control and economics, in particular, is needed. He found that only two of the 533 scientific publications about *Salmonella* and pork dealt with economics. Hence, a multidisciplinary approach, combining the fields of epidemiology, economics, veterinary aspects and policy, should be applied more thoroughly. New publications that became available during the research for this thesis have sometimes led to new insights that have been included in the thesis. Consequently, in the subsequent chapters in the thesis, input data and as a consequence also the output, may vary due to new insights. The differences in output were not dramatic.

2.3 Modelling designs

In this section the construction of the models is discussed. As explained in the previous sections, a stochastic epidemiological simulation model and a deterministic economic model were designed. For the epidemiological model, the SIR-modelling approach is used. SIR-modelling is a generally accepted approach in epidemiology (e.g. De Jong, 1995). With respect to *Salmonella*, a pig (alive or carcass) can be in different states and can switch between states over time. The basic design with six states for live pigs and four states for carcasses was based on literature and approved by experts (Chapters 2 and 3).

The basic design can be described as follows: groups of individuals enter a stage with a certain distribution over the different states. The sojourn time in a stage determines how many times the group will run through a matrix with transition probabilities. The output of the model is the distribution over the different states at the end of each stage. The transition probabilities can change due to interventions and measures. The design is common in nature and flexible, so it can also be applicable for other pathogens in the pork chain and even for pathogens that spread in other supply chains. Due to the limited data available, completion of this basic design, i.e. determining the number of states and the value or equations of the probabilities in the transition matrix is the hardest part. This aspect is difficult since a lot of information is lacking or ambiguous. It should be noticed that the purpose of the model is to gain insight into the epidemiological effects of different strategies to improve the food safety of pork, which makes it possible to support decision-making. For supporting decision-making however, the priority setting is more important than exact values. Obviously, for the model the best possible assumptions are used.

It appeared that the literature provided more information and more experts were able to answer questions about the epidemiology of *Salmonella* at finishing farms than about the other stages. This can imply that the finishing stage is regarded as important in *Salmonella* control. The sojourn time in the finishing stage is relatively long (3 months versus several hours in the transport, lairage and slaughter stages). As a result, the modelling of the finishing stage is more detailed than the modelling of the stages of multiplying, transport, lairage and slaughtering. The results of the research described in this thesis showed that besides the finishing stage, the slaughtering stage is also very important to reduce the prevalence of contaminated carcasses. As soon as more information about the epidemiology of *Salmonella* in other stages in the pork chain becomes available, the model can be adjusted to improve the input and design and consequently the output of the model.

The economic model was developed in function of the epidemiological model and is simple and straightforward. For each intervention or measure the costs and returns are calculated using literature and expert knowledge from the people from feed manufacturers, companies that build slaughterhouses, etceteras. In the case that the costs or returns were not known, e.g. because the intervention did not exist yet or data was limited, an estimation was made. The economic model focussed on the costs of control measures and a few benefits have been included. A more detailed approach, including the indirect benefits such as improved production results or increased value of the products supplied by each stage would be a useful addition in future research. Such a research might only involve the finishing stage and the slaughtering stage, as these stages are the most important.

In future models to support decision-making in the supply chain, it would be desirable to study the possibilities of integrating the epidemiological and the economic models An integrated model enables the exploration of more control strategies and what-if scenarios including dynamic financial incentives, such as variable penalties. The insight and knowledge gained from research as described in this thesis can be helpful for future integrated models. For example, the effectiveness of a control system with Maximum Acceptable Prevalence levels and an accompanying payment system could be evaluated over time. In the research described in this thesis, the first exploration has been carried out and concludes that control by such a payment system is promising. The next step is to select the most appropriate Maximum Acceptable Prevalence levels and the payment differentiation given predefined aims. For an integrated model even more input data are required, such as the indirect and direct relations and interactions between epidemiological and economic variables. An extended verification, validation and sensitivity analysis would be inevitable and the output of such a model has to be interpreted carefully.

2.4 Verification and validation of the models

The third step in simulation modelling is model verification and validation. Verification deals with building the model correctly and validation deals with building the correct model (Banks, 1998). With complex models in particular, such as *Salmonella* in the pork chain, verification is essential. To verify if the conceptual model is translated correctly into a computer model, several techniques can be used. For both the epidemiological and the economic model, two of the techniques described by Law and Kelton (2000) have been used. First, the simulation model has been run under a variety of settings of the input parameters to check if the output matches with the available knowledge and expectations.

Second, the model has been run under simplified assumptions. In this case, this meant that each stage was run separately to evaluate whether the model produced the expected output. By splitting the complex chain model in parts, the model is more comprehensible

Validation of the epidemiological model was complicated. No real data were available for validation of the entire simulation model. Therefore, comprehensive sensitivity analysis has been carried out. Sensitivity analysis can support validation (Kleijnen, 1999), since the purpose of validation is to determine whether the simulation model is an acceptable representation of the real system. Design Of Experiments is a useful technique to perform a sensitivity analysis of a model with many input variables and gives insight into the validity of the model (Kleijnen, 1999). In order to design valid models, a close interaction between the model design and actual life experiments is essential. For useful what-if scenarios and decision support, a valid model is a condition. The validation of the economic model has been performed using available data and by face validity. The results of the economic model were presented and validated by experts in the field.

2.5 Results and applications

The fourth and last step of simulation modelling is to produce and analyse results. The results showed that control in the slaughtering and finishing stages contributes most to the reduction of the final prevalence of contaminated carcasses. Swanenburg (2000) also concluded from a field experiment that in general the slaughtering stage contributes most to the final prevalence of bacteriologically contaminated carcasses. The finishing stage contributes more to the contamination of livers and tongues that are also used for human consumption. The results of Swanenburg (2000) are based on determination of the type of *Salmonella*. In the model described in this thesis, no distinction is made between different *Salmonella* types. Decision-makers are interested in the best, most cost-effective way to improve food safety and in principle, all *Salmonella* types are a risk with respect to food safety. From the point of view of governmental decision-makers, it does not really matter which stage prevents the contamination of the carcass, as long as the contamination is prevented in a cost-effective way. The scenarios studied in Chapter 4 have demonstrated that observing several stages in the chain at the same time results in another priority-setting than observing one stage at the time. This is an important conclusion for decision-makers. Cost-effectiveness is largest in the finishing stage and the slaughtering stage. To improve the cost-effectiveness, all participants in a stage should join the control programme. A system is needed to motivate the individual participants to prevent and reduce *Salmonella* at their individual farm or firm in order to prevent free rider behaviour.

In Chapter 5, a system is explored to encourage each participant to invest in *Salmonella* control. The system had two main aspects: segmentation of batches by Maximum Acceptable Prevalence levels and variable revenues per segment of batches. This approach is promising, since the (negative financial) impact is the largest for participants with the worst performance. With such a system the incentives can be put at the stages where they are most needed to improve performance. Explorations with models give insight into the possible effects of such systems. The refinement of a system in practice is a part of a total control programme for the pork chain, which must be designed with care. A control programme needs to have the right balance between costs of the programme and the reduction of the food safety risk.

3 Costs and benefits in the pork supply chain

Since it is not possible to include every interesting aspect in a thesis, some aspects remain underexposed. One aspect that should be mentioned in particular is the distribution of costs and benefits over the chain participants in order to improve the overall chain performance. This aspect is a very complex one, but for the feasibility of *Salmonella* control it requires attention. The costs for adequate *Salmonella* control from finishing to slaughter can amount to up to € 5.50 per pig, which is 4% of the total production costs. It may occur that some of the chain participants take the rap for the costs, while other cash the financial benefits (Ingenbleek, 2003a). It does not need explanation that disregard of the distribution of costs and benefits results in discouragement of chain participants and a low overall chain performance. Farms and firms in supply chains compete both with colleagues at the same stage in the chain and their chain competes with other chains within the same sector (Ingenbleek, 2003a). Although this thesis has focused on the costs, future research should also include the benefits. The price a chain participant receives for a product depends on the (added) value of the supplied product and not solely on the production costs of the product. To increase the value of their products, chain participants can choose to participate in another chain or to co-operate with colleagues. In the next paragraph three types of value are discussed.

Value can be created in three ways (Ingenbleek, 2003b): business economic value, customer value and societal value. Reduction of *Salmonella* in the pork chain deals with all three values. First, the value of business economics deals with the production costs and is based on increasing the efficiency resulting in lower cost price and consequently in higher margins. Many control measures in the pork chain to reduce and prevent *Salmonella* contamination are general in nature and can also result in a reduction of the cost price. For instance, improved hygiene in the finishing stage results in improved animal health that can increase the daily weight gain or reduce the veterinary costs. Customer value is the direct selling price. This price is based on adding value that is appreciated and paid for by customers and may result in a larger market share, i.e. new products or additional service combined with a product. The final customer of the pork supply chain is the consumer and it has appeared that an additional food safety label with respect to *Salmonella* might result in a greater willingness to pay (Boland et al., 1999). Societal value is based on added value incorporated in aspects appreciated by the governments or society (e.g. European subsidies or fiscal advantages for investments). The government has its responsibility to protect its citizens and food safety is an issue that affects the entire society. Moreover, reduction of food borne illness directly reduces societal costs, such as hospitalisation and reduced labour productivity. Future research should consider the possibilities of creating additional value and a fair distribution of costs and benefits. Therefore also the stages after the slaughtering stage must be included. Besides the direct costs of control measures, additional costs turn up such as recalls (Teratanavat and Hooker, 2003).

4 Practical application: checklists for farm specific control

Practical implications of the scientific research described are not out of sight. After completing the survey in 2001 and literature research, many possible measures for the finishing stage to control *Salmonella* were listed. The main control measures were selected and included in the economic model to calculate the control costs for an average finishing farm. However, in practice there is a lot of variation in housing systems, feeding strategies and management between farms. For an effective control of *Salmonella* in practice, these differences in finishing farms have to be taken into account. A pilot research project has been carried out with two aims. The first aim was to develop a user-friendly checklist to select the appropriate farm specific control measures to reduce the introduction and spread of *Salmonella*. The second aim was to carry out a small-scale field research in practice to get an idea about the effectiveness of implementing the farm specific measures advised by completing the checklist (Van der Gaag et al., 2003). If the checklist appeared to be a useful tool, it could be used for the finishing stage as a part of a *Salmonella* control programme.

4.1 Development of the checklist

The checklist had to be simple, user-friendly, cover all farm processes and completion should not take too much time. To fulfil all these requirements, seven checklists designed as decision trees have been developed and each checklist deals with a part of the management or working procedures of the finishing farm. The checklists are: 'supply of piglets', 'supply of drinking water', 'supply of pelleted feed', 'supply of cereals and roughage', 'supply of by-products', 'hygiene management' and 'daily management'. Each checklist contained possible control measures. The result of completing all checklists is a list with the farm specific control measures. The checklists have been developed for specialised finishing farms.

4.2 Testing the checklists at finishing farms

Three finishing farms that were tested positive for *Salmonella* in the autumn of 2001 by the Animal Health Service in the Netherlands were included in the pilot. Each farm completed the checklists and implemented a part of the advised control measures during eight months. Pigs at slaughter weight were tested bacteriologically by faecal samples at the farm and serologically by collecting and blood samples at the slaughterhouse (analysed with a mixed ELISA, OD10%) in May 2002, August 2002 and November 2002. At the end of the eight months, the farmers completed an evaluation form with 28 statements in order to get insight into the opinion of the farmers about the checklists and the advised control measures.

4.3 Results of the field research

Although all farms showed high prevalence of *Salmonella* in autumn 2001, at the beginning of the field research almost all samples of two farms were negative for *Salmonella*. An explanation for one of these farms may be that the farm had already started to implement control measures (disinfecting after cleaning the compartment) in the winter of 2001 after the results of the Animal Health Service had been communicated. At the third farm, almost 50% of the blood samples were positive for *Salmonella* and this percentage decreased over time, after implementing advised control measures.

The number of advised control measures varied between 34 and 39. Some measures were advised to all farms, e.g. cleaning and disinfecting of the compartment after selling the pigs to the slaughterhouse, cleaning silo for restoring feed, strict all in – all out per compartment, avoiding that pigs from different ages have to walk the same route and look after the pigs in the sick bay at the end of the working day. Some examples of control measures that were advised only to one or two farms were: testing quality of drinking water, more sanitary procedures for removing cadavers, prevent existence of feed remains in troughs and acidify drinking water.

The farmers experienced that the checklists were useful to determine weak points and control measures with respect to *Salmonella* in a farm in a structured way. All farmers indicated that they thought that the management at their farm improved and they intended to continue with the implemented control measures. It appeared to be difficult to apply the measures consistently. However, when a hygiene measure is carried out most of the time instead of permanently, it may be ineffective. Farmers were familiar with most control measures although they were not aware of the reducing effect on the introduction or spread of *Salmonella*.

4.4 Conclusions of the field research

In conclusion, the checklists form a promising tool to help individual farms to detect the best control measures for their farm. The results showed that some general measures were the same for all three participating farms and some measures were advised only to one or two farms. Hence, a more farm-specific package of control measures is advised which can reduce the costs. Despite their positive response, the farmers are not willing to pay for advice with respect to *Salmonella* reduction since *Salmonella* is not (yet) an important issue for finishing farmers. The motivation of farmers to invest in *Salmonella* control is limited, which should be taken into account of while introducing a control programme. It may be expected that implementing control measures can increase the health status of the farm since many measures against *Salmonella* are general in nature and are also effective against other pathogens. The duration of this research and the number of farms have been too small to find differences in production results. However, a higher health status could improve production results such as daily weight gain and feed conversion, fat-meat ratio and percentage of abnormal livers. A more extended field research with the checklists developed should be carried out in order to investigate the costs and benefits of specific *Salmonella* control at finishing farms.

5 Main conclusions

With the research described in the thesis the insight into epidemiological and economic effects of different strategies to improve food safety in the pork chain with respect to *Salmonella* has increased. The multidisciplinary approach to the problem, combining the fields of epidemiology, economics, veterinary science and policy making has contributed to this insight. The following conclusions have been drawn:

- Experts have indicated that to improve food safety of pork, reduction of the <u>spread</u> of *Salmonella* in the supply chain is more effective than reduction of the <u>introduction</u> of *Salmonella.*
- The research has revealed the importance of a chain approach instead of considering each stage individually. Regarding costs and prevalence reduction per stage, cost-effectiveness of *Salmonella* control is highest in the lairage. However, regarding costs in the supply chain and prevalence reduction of *Salmonella* in the end product (the chain approach), cost-effectiveness of *Salmonella* control is highest in the slaughtering and finishing stages.
- Care is needed in selecting the stage in the supply chain where control measures are implemented since not all possible investments in control measures in the supply chain influence the final prevalence of contaminated carcasses.
- The implementation of packages of control measures in both finishing and slaughtering stages costs on average about € 4.40 per pig. If every stage in the supply chain implements control measures to minimise the prevalence of contaminated carcasses the costs amount to € 5.50 per pig excluding monitoring costs. Most control measures to prevent or reduce *Salmonella* in the pork chain are general in nature and may have a reductive effect on other pathogens as well. Hence, the costs should not be attributed only to *Salmonella* control.
- The effectiveness of *Salmonella* reduction depends on the efforts of all participants in a stage. The relation between the percentage of chain participants that make efforts to reduce the *Salmonella* prevalence and the final prevalence of contaminated carcasses is not linear. In other words, a small number of poorly performing participants can disproportionately reduce the effectiveness of the efforts of the other participants.
- Determining only a maximum acceptable prevalence in the long term (i.e. a year) does not prevent highly contaminated batches of carcasses finding their way to the consumer. The reason is that relatively small number of highly contaminated batches will have a negligible effect on the average prevalence in the long term.

- Preventive measures are preferable to control *Salmonella* in the pork supply chain. Corrective control measures can be kept in reserve in case the preventive measures fail.
- A payment system based on the *Salmonella* prevalence of the supplied animals or carcasses is a promising strategy to improve food safety.
- The ideal *Salmonella* control programme does not exist, but the concept of strategic management offers a structured model to design the basis for a *Salmonella* control programme.
- It would be helpful if a uniform testing procedure for all pork supply chains were to be implemented in member states of the European Union.

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Summary

1 Introduction

Interest in food safety has increased considerably over recent decades. The bacteria *Salmonella* are the major source of food borne illness with over 50,000 human cases in the Netherlands per year. Human salmonellosis results in high societal costs, such as reduced productivity, treatment, hospitalisation and premature death. For human salmonellosis in the Netherlands, these costs are estimated between 32 and 90 million Euro per year. Consumers mostly associate *Salmonella* with poultry and eggs, however 25% of human cases of salmonellosis are caused by serotypes that occur in pigs. Hence, pork can be regarded as an important source for food borne salmonellosis. *Salmonella* bacteria are ubiquitous in nature and can be introduced and spread in every stage of the pork supply chain and cause a risk for food safety. As a consequence, the entire supply chain should be included in the control of *Salmonella*. The goal of *Salmonella* control is to reduce the prevalence of contaminated pork products. The basic end product of the pork supply chain is a chilled carcass. Carcasses are further processed as fresh pork products or prepared as fermented or cooked products. Thus, to improve food safety with respect to pork, a reduction of the number of contaminated carcasses needs first attention.

For several stages of the Dutch pork supply chain the *Salmonella* prevalence has been estimated. The average prevalence of *Salmonella* in the entire finishing pig population in the Netherlands is 25% and *Salmonella* is present in about 90% of all Dutch pig farms (serological testing for antibodies at cut-off %OD>10). In general, *Salmonella* infections occur sub-clinically in pigs, which means that pigs do not get ill. By careful slaughtering it is possible that an infected pig ends up as a contaminated carcass. At the slaughterhouse, the average prevalence of contaminated carcasses is estimated at about 2%. In 2000 18.8 million pigs were slaughtered in the Netherlands, which indicates that in 2000 over 350,000 contaminated carcasses entered the food chain. The prevalence of contaminated carcasses may be underestimated since the internationally accepted testing procedure is not the most sensitive test available. To control a pathogen brings costs and since the margins in the pork chain are small, it is essential to get insight into the cost-effectiveness of different control strategies.

The objective of this research is to gain insight into the epidemiological and economic effects of different strategies in the finishing, transport, lairage and slaughtering stages to improve the food safety of pork with respect to *Salmonella*.

The research included four phases that are described in section 2 through 5 of the summary:

- Exploration of possible measures that can be implemented in the pork supply chain to control the introduction and reduce the prevalence of *Salmonella* in the end product;
- Development of two simulation models; an epidemiological model to simulate introduction and spread of *Salmonella* in the pork supply chain and an economic model to evaluate the economic consequences of control measures;
- Obtaining insight into the cost-effectiveness of *Salmonella* control in the pork supply chain;
- Formulation of future strategies in the pork supply chain with respect to control of *Salmonella*.

Section 6 presents the main conclusions of the research in this thesis.

2 Expert elicitation in the Netherlands and Denmark

Literature on the effects of control on the infection dynamics of *Salmonella* and on the costs of control is scarce. To collect information on possible control measures and on details of the course of infection and contamination, a survey of experts was carried out (Chapter 2). The survey was carried out with Dutch and Danish experts in the field of *Salmonella* and concerned the entire pork supply chain. The objectives of the survey were to determine and rank control measures. An additional objective was to compare the opinions of experts from different countries and with different backgrounds. In total 75 mail surveys were send to experts. The response rate was over 50%. The results showed that the stages, which were expected that control measures in reducing Salmonella in pork would be most effective, were the finishing and slaughtering stages.

The preferred control measures in the finishing stage were providing acidified feed and preventing the spread of *Salmonella* within the farm. The slaughtering stage should focus on preventing cross-contamination during slaughter. The differences in the opinions of respondents from different backgrounds were mainly reflected by the relative importance given to specific management interventions. For instance, the Danish respondents attached more importance to the purchase of *Salmonella* free piglets in the finishing stage and to logistic slaughter. Respondents with a research background seemed to attach most importance to interventions that were also presented in recent literature, such as feeding non-heated grain to finishing pigs.

3 Development of simulation models

The knowledge about the interaction and relations between the epidemiological and economic aspects was limited. Therefore, two separate models were designed, one for the epidemiological aspects and one for the economic aspects of *Salmonella* control in the pork supply chain. These models form the core elements of the thesis.

3.1 The epidemiological model

The epidemiological model to simulate the introduction and spread of Salmonella in the pork supply chain is a detailed stochastic state transition model (Chapter 3). For this model, the SIR-modelling approach has been used (SIR stands for Susceptible, Infectious, Recovered), which is a generally accepted approach in theoretical epidemiology. With respect to *Salmonella*, a pig (alive or carcass) can be in several states and can switch between states over time. The switch between states depends on two components: number of animals per state and transition probabilities in a time-dependent matrix. The transition probability gives the probability for an animal moving from one state to another in one time step.

The time step used in the model equals one day. The sojourn time in a stage determines how many times the group will run through a matrix with transition probabilities. The transition probabilities can change due to interventions and measures. Based on literature and approved by experts, six different states were distinguished for live pigs. After the animal is killed in the slaughterhouse some transitions, such as seroconversion, are impossible and for carcasses four different states are distinguished. The basic unit of the model is a group of 100 animals that moves as one unit through the entire model. In each stage one or more farms or firms can be present. A group is accommodated in one compartment in the finishing stage, then transported in one truck to the slaughterhouse, and kept together in the lairage. The pigs from one group are slaughtered in random order and remain in this order during the slaughter and chilling process. The output of the epidemiological model is the distribution of each group over the states per stage or in other words, the *Salmonella* prevalence per farm or firm in each stage.

3.2 The economic model

The economic model is a deterministic simulation model. For each control measure in the finishing to slaughtering stages, the costs and revenues have been calculated using the technique of partial budgeting. The calculations of the net costs are based on typical Dutch farms and firms. The parameters of the model can be adjusted to reflect other types of farms or firms. For the finishing stage, the net costs in Euro per pig are calculated for a traditional specialised finishing farm with 2000 pig places (2 stables with 10 compartments each). For the transportation stage, an average truck transports 100 finishing pigs per trip and rides 12 trips per week. The slaughterhouse (including lairage and slaughtering) used for the calculation, processes 600 pigs per hour and 1.5 million per year. The lairage can accommodate 1800 pigs. In the basic situation the evisceration is executed by hand and the slaughterline is cleaned at the end of each working day. The carcasses are not decontaminated (e.g. by spraying lactic acid or steam over carcasses at the end of the slaughterline), since decontamination is not allowed in the European Union for fresh meat.

Since it is not feasible in practice to implement all possible control measures, for each stage a package of measures has been defined by selecting feasible measures, which in the main do not overlap each other (Chapter 4). The net costs for these packages per stage were calculated per pig. In the finishing stage, the net costs for the control package are € 2.99, for the transportation stage € 0.65, for the lairage € 0.40 and for the slaughtering stage € 1.47.

4 Cost-effectiveness of *Salmonella* control

Combining the results of the epidemiological and the economic models allowed comparison of the cost-effectiveness of different control strategies for *Salmonella* in stages of the pork supply chain (Chapter 4). For each control strategy a package of control measures was implemented in one or more stages of the four stages of finishing, transport, lairage and slaughtering. Each stage had the option of implementing the package of control measures or not. Cost-effectiveness was calculated by dividing the reduction of the prevalence by the total net costs per pig. To compare a chain approach with a stage approach, first the cost-effectiveness of implementing control measures in only one stage was calculated by dividing the reduction in prevalence in that particular stage by the net costs per pig of the package of control measures. The implementation of control in the lairage appeared to have the highest cost-effectiveness. However, using a chain approach, control in the slaughtering stage and the finishing stage appeared to be most cost-effective.

If all four stages implement the package of control measures the costs are € 5.50 per pig. This is about 4% of the total costs of raising and slaughtering a pig, which is relatively high. It should be realised that a high prevalence batch causes a higher risk for food borne diseases when the batch is sold for fresh meat products than when the batch is processed into cooked, salted or fermented meat products. These processing steps are in fact some kind of decontamination since they largely eliminate Salmonella bacteria. From this point of view, the prevalence per batch could with benefit be used to the purpose of the batch. Hence, a possible regulation to improve the food safety of pork with respect to *Salmonella* is to define a Maximum Acceptable Prevalence (MAP) of contaminated carcasses per slaughtering firm (Chapter 5). It would then be possible to define one MAP for batches of carcasses for fresh meat-products and a different MAP for batches for processed meat products. The revenues for batches of carcasses that exceed a MAP would likely be lower than for batches below the MAP. In general, the principle of segmentation of revenues based on MAP is a promising basis for regulation to improve the food safety of pork with respect to *Salmonella*.

In Chapter 5, it was assumed that there are four different possibilities to control *Salmonella* in each stage: no control, preventive control, corrective control or total control. Preventive control implies control measures are continuously implemented in that stage to prevent the introduction or spread *Salmonella*. Corrective control is only implemented temporarily after the prevalence in a stage exceeds a predefined prevalence. Total control includes both preventive and corrective control. When the testing costs are high, preventive control measures are preferable to control *Salmonella* in the pork chain. Under the assumptions in this thesis, total control (preventive and corrective) is less cost-effective than only preventive control.

5 Feasibility of *Salmonella* control programmes in the pork chain

Strategic management principles have been applied to define the aspects that are important for the design and implementation of a *Salmonella* control programme in a pork supply chain (Chapter 6). The theoretical steps in strategic management provide a structured approach to the design of such a programme. Four steps should be taken: formulate a mission and objectives, perform an internal audit, perform an external audit, and formulate and select possible strategies. As an example, two *Salmonella* control programmes for the Dutch pork supply chain were designed: a Food Safety Programme and a Competitive Programme. The Food Safety Programme focused entirely on food safety. To guarantee that the prevalence of contaminated carcasses per batch of 1000 carcasses is low, the number of samples has to be very high. Hence, this is not a very feasible programme since only the costs for testing already count up to 3 Euro per pig. The Competitive Programme aims to be comparable with the programme of major competitors and, in the long term, to overtake competitors. The Competitive Programme is cheaper and principally feasible, although it is based on the programme of another country. By the introduction of such a programme, the strengths of the Dutch pork supply chain and the opportunities in the Netherlands may be not fully exploited.

The challenge is to design a programme that achieves the right balance between the costs of the programme and to the reduction of the risk to food safety. To emphasise food safety and to prevent each country from establishing its own testing procedure, a uniform testing procedure for all members of the European Union would be a good case.

6 Main conclusions

With the research described in the thesis the insight into epidemiological and economic effects of different strategies to improve food safety in the pork chain with respect to *Salmonella* has increased. The multidisciplinary approach to the problem, combining the fields of epidemiology, economics, veterinary science and policy making has contributed to this insight. The following conclusions have been drawn:

- Experts have indicated that to improve food safety of pork, reduction of the spread of *Salmonella* in the supply chain is more effective than reduction of the introduction of *Salmonella.*
- The research has revealed the importance of a chain approach instead of considering each stage individually. Regarding costs and prevalence reduction per stage, cost-effectiveness of *Salmonella* control is highest in the lairage. However, regarding costs in the supply chain and prevalence reduction of *Salmonella* in the end product (the chain approach), cost-effectiveness of *Salmonella* control is highest in the slaughtering and finishing stages.
- Care is needed in selecting the stage in the supply chain where control measures are implemented since not all possible investments in control measures in the supply chain influence the final prevalence of contaminated carcasses.
- The implementation of packages of control measures in both finishing and slaughtering stages costs on average about € 4.40 per pig. If every stage in the supply chain implements control measures to minimise the prevalence of contaminated carcasses the costs amount to € 5.50 per pig excluding monitoring costs. Most control measures to prevent or reduce *Salmonella* in the pork chain are general in nature and may have a reductive effect on other pathogens as well. Hence, the costs should not be attributed only to *Salmonella* control.

- The effectiveness of *Salmonella* reduction depends on the efforts of all participants in a stage. The relation between the percentage of chain participants that make efforts to reduce the *Salmonella* prevalence and the final prevalence of contaminated carcasses is not linear. In other words, a small number of poorly performing participants can disproportionately reduce the effectiveness of the efforts of the other participants.
- Determining only a maximum acceptable prevalence in the long term (i.e. a year) does not prevent highly contaminated batches of carcasses finding their way to the consumer. The reason is that relatively small number of highly contaminated batches will have a negligible effect on the average prevalence in the long term.
- Preventive measures are preferable to control *Salmonella* in the pork supply chain. Corrective control measures can be kept in reserve in case the preventive measures fail.
- A payment system based on the *Salmonella* prevalence of the supplied animals or carcasses is a promising strategy to improve food safety.
- The ideal *Salmonella* control programme does not exist, but the concept of strategic management offers a structured model to design the basis for a *Salmonella* control programme. It would be helpful if a uniform testing procedure for all pork supply chains were to be implemented in member states of the European Union.

Samenvatting

1 Introductie

De laatste decennia is de aandacht voor voedselveiligheid in het algemeen en voor zoonosen in het bijzonder sterk toegenomen. Een zoonose is een pathogeen dat van dier op mens kan overgaan, bijvoorbeeld via de consumptie van dierlijke producten. Een belangrijke zoonose is de bacterie *Salmonella*. Er zijn in Nederland jaarlijks meer dan 50.000 voedselgerelateerde menselijke gevallen van salmonellose. De maatschappelijke kosten tengevolge van salmonellose in Nederland worden geschat tussen 32 en 90 miljoen Euro per jaar. Onder maatschappelijke kosten vallen verminderde arbeidsproductiviteit, medicatie, ziekenhuisopname en vroegtijdig overlijden van mensen. Er zijn meer dan 2400 typen *Salmonella* bekend die in principe allen pathogeen zijn, maar lang niet alle soorten komen voor in Nederland. Consumenten associëren *Salmonella* veelal alleen met pluimvee- of eierproducten, maar ongeveer een kwart van alle menselijke gevallen van salmonellose wordt veroorzaakt door typen die bij varkens voorkomen. Varkensvlees is zodoende een belangrijke oorzaak van menselijke salmonellose.

Salmonella kan in iedere schakel van de varkensvleesketen (van varkensfokkerij tot consument) binnenkomen en zich verspreiden. Met het oog op het verbeteren van de voedselveiligheid van varkensvlees is het daarom van belang de hele varkensvleesketen te betrekken bij het beheersen van *Salmonella*. Het basis eindproduct dat de varkensvleesketen oplevert, is een gekoeld karkas. De karkassen vormen de basis voor vers vleesproducten of worden verder bewerkt tot verhitte of gefermenteerde vleesproducten. Daarom dient de eerste aandacht uit te gaan naar een afname van het aantal karkassen dat gecontamineerd, oftewel besmet, is met *Salmonella*.

Uit een prevalentiestudie uit 1999 bleek dat in Nederland ongeveer 25% van de vleesvarkenspopulatie besmet is (geweest) met *Salmonella* en dat *Salmonella* voorkomt op 90% van de varkensbedrijven. Normaliter verloopt een *Salmonella* besmetting bij varkens sub-klinisch. Lang niet ieder varken dat in zijn leven in aanraking komt met de bacterie zal na het slachten een gecontamineerd karkas opleveren. De prevalentie van gecontamineerde karkassen is geschat op 2%. Bij 18 miljoen geslachte varkens per jaar betekent dit dat er jaarlijks meer dan 350.000 met *Salmonella* gecontamineerde karkassen richting consument gaan. Het percentage gecontamineerde karkassen wordt mogelijk onderschat omdat de internationaal geaccepteerde testmethode niet zeer gevoelig is.

Het beheersen van *Salmonella* brengt kosten met zich mee en de marges in de varkensvleesketen zijn klein. Het is daarom van belang om inzicht te krijgen in de kosteneffectiviteit van beheersstrategieën. Het doel van dit onderzoek is inzicht verkrijgen in de epidemiologische en economische gevolgen van verschillende *Salmonella* beheersstrategieën om de voedselveiligheid van varkensvlees te vergroten. Hierbij richt het onderzoek zich op de schakels vleesvarkenshouderij, transport, wachtruimte en slachterij. Het onderzoek is onder te verdelen in de volgende vier stappen die afzonderlijk in deze samenvatting worden beschreven in paragrafen 2 tot en met 5:

- Verkenning van de mogelijke beheersmaatregelen in de varkensvleesketen om de introductie en verspreiding van *Salmonella* te voorkomen en de prevalentie te verlagen.
- Ontwikkeling van twee simulatie modellen: een epidemiologisch model om de introductie en verspreiding van *Salmonella* in de varkensvleesketen te simuleren en een economisch model om de economische gevolgen van beheersing te verkennen.
- Inzicht verkrijgen in de kosteneffectiviteit van *Salmonella* beheersing in de varkensvleesketen.
- Formulering van toekomstige strategieën om *Salmonella* in de varkensvleesketen te beheersen.

In de laatste paragraaf van de samenvatting worden de belangrijkste conclusies van het onderzoek gepresenteerd.

2 Raadplegen van deskundigen uit Nederland en Denemarken

Er is slechts in beperkte mate literatuur beschikbaar over de effecten van beheersmaatregelen op het infectie- en besmettingsverloop. Om hier meer inzicht in te krijgen en om tevens het belang van mogelijke beheersmaatregelen in te schatten is een expertonderzoek uitgevoerd (hoofdstuk 2 van het proefschrift). Er zijn 75 Nederlandse en Deense deskundigen op het gebied van *Salmonella* in verschillende schakels van de varkensvleesketen benaderd om mee te werken. Het doel van het expertonderzoek was om mogelijke beheersmaatregelen per schakel te bepalen en rangschikken. Een tweede doel was om experts uit verschillende landen en met verschillende achtergronden te vergelijken. De respons was ruim 50%. De experts gaven aan dat de schakels vleesvarkenshouderij en slachterij de belangrijkste schakels zijn om *Salmonella* in het eindproduct te verminderen.

De beste beheersmaatregelen in de vleesvarkenshouderij zijn: aangezuurd water of voer verstrekken en het voorkomen dat *Salmonella* zich kan verspreiden binnen het bedrijf, bijvoorbeeld door all in – all out toe te passen en goede hygiëne in acht te nemen. In de slachterij is het voorkomen van kruiscontaminatie het belangrijkst wat vooral door hygiëne maatregelen en zorgvuldige slachttechnieken kan worden bewerkstelligd. Ten opzichte van de Nederlandse respondenten hechtten de Deense respondenten meer belang aan de aankoop van *Salmonella* vrije biggen in de vleesvarkensschakel en aan logistiek slachten in de slachterijschakel. Respondenten met een onderzoeksachtergrond benoemen vooral veel maatregelen die in recente literatuur verschenen zijn, zoals het verstrekken van niet-verhit graan aan vleesvarkens.

3 Ontwikkeling van simulatiemodellen

Omdat er weinig bekend is over de relaties en interacties tussen epidemiologische en economische aspecten van *Salmonella* beheersing, is gekozen voor het ontwikkelen van twee aparte modellen: een epidemiologisch model en een economisch model. Deze modellen vormen de kern van het proefschrift.

3.1 Het epidemiologische model

Het epidemiologische model is een gedetailleerd stochastisch model (hoofdstuk 3). Het model is gebaseerd op de in de theoretische epidemiologie algemeen geaccepteerde SIR benadering (SIR staat voor Susceptible, Infectious, Recovered). Deze benadering gaat ervan uit dat een dier zich in verschillende infectiestadia kan bevinden en dat het mogelijk is om binnen een tijdstap van het ene stadium naar een ander stadium over te gaan. De tijdstap in het model is één dag. Of een varken in een ander stadium komt hangt af van de overgangskans die is gedefinieerd. Deze kans hangt mede af van de beheersmaatregelen die in een schakel zijn genomen. Voor *Salmonella* besmettingen bij varkens zijn in het epidemiologische model zes verschillende stadia gedefinieerd die aangeven of een varken serologisch en bacteriologisch positief is. Als het varken wordt geslacht zijn bepaalde overgangen en twee stadia niet meer mogelijk. Zo kan een dood dier niet meer van serologische status veranderen. Daarom zijn voor het karkas vier verschillende stadia beschreven.

In het model wordt ervan uitgegaan dat in de varkensvleesketen groepen van 100 varkens bij elkaar blijven van opleg in de vleesvarkensfase tot aan de slachterij. In de slachterij worden de dieren uit één groep in willekeurige volgorde geslacht. Het epidemiologische model geeft als uitkomst de prevalentie van iedere groep aan het eind van iedere schakel bij een bepaalde beheersstrategie in de keten.

3.2 Het economische model

Het economische model is een deterministisch simulatie model. Voor iedere beheersmaatregel in de schakels vleesvarkenshouderij, transport, wachtruimte en slachterij zijn de kosten en opbrengsten per varken geschat met behulp van de 'partial budgeting' methode. Voor iedere schakel is een voorbeeldbedrijf beschreven dat als basis dient voor de berekeningen. De gegevens die voor het model gebruikt worden kunnen eenvoudig worden aangepast om ook voor andere typen bedrijven de kosten en opbrengsten te berekenen. In het model is uitgegaan van een vleesvarkensbedrijf met 2000 varkensplaatsen en van een transporteur met vrachtwagens voor 100 vleesvarkens die per week 12 keer een vracht naar de slachterij brengen. Het slachthuis in het model slacht 1,5 miljoen varkens per jaar en bestaat uit een wachtruimte voor 1800 varkens en een slachtlijn die 600 varkens per uur slacht. Er vindt geen decontaminatie van karkassen plaats, omdat de Europese Unie dit verbiedt.

Aangezien het in de praktijk financieel niet haalbaar is om alle mogelijke beheersmaatregelen in te voeren, is voor iedere schakel één pakket maatregelen samengesteld. In dit pakket zitten maatregelen die haalbaar en toegestaan zijn en elkaar niet te veel overlappen (hoofdstuk 4). Voor de vleesvarkenshouderij zijn de netto kosten van het pakket beheersmaatregelen € 2,99 per varken, voor de schakel transport komt het pakket neer op € 0,65 per varken, voor de wachtruimte op € 0,40 en voor de slachterij € 1,47.

4 Kosteneffectiviteit van *Salmonella* beheersing

Als de resultaten van beide modellen worden samengevoegd is het mogelijk om de kosteneffectiviteit van verschillende beheersstrategieën te vergelijken (hofdstuk 4). Een beheersstrategie geeft aan welke schakels het pakket beheersmaatregelen hebben ingevoerd. Gegeven een bepaalde beheersstrategie rekenen beide modellen uit wat dat voor consequenties heeft op de prevalentie en de kosten per varken. De basis beheersstrategie is dat geen van de schakels het pakket maatregelen implementeert en alle andere beheersstrategieën worden hiertegen afgezet. De kosteneffectiviteit van een beheersstrategie wordt berekend door de verandering in prevalentie te delen door de verandering in netto kosten.

De benadering per schakel is vergeleken met een ketenbenadering. De schakelbenadering gaat ervan uit dat de verandering in prevalentie wordt berekend door de prevalentie aan het eind van een schakel met een beheersstrategie te vergelijken met de prevalentie aan het eind van die schakel in de basis strategie. De ketenbenadering gaat altijd uit van de prevalentie in de laatste schakel. Op deze wijze kan de kosteneffectiviteit van een beheersstrategie zowel per schakel als per keten worden berekend. Met de schakelbenadering was de kosteneffectiviteit van beheersing in de wachtruimte het grootst. Daarentegen was de kosteneffectiviteit met de ketenbenadering het grootst in de schakels slachterij en vleesvarkenshouderij. Aangezien het bij voedselveiligheid uiteindelijk gaat om het eindproduct is een ketenbenadering een betere benadering.

Als alle vier de schakels het pakket beheersmaatregelen implementeren, zijn de totale netto kosten € 5,50 per varken. Dit is met ongeveer 4% van de totale productiekosten om een varken groot te brengen en te slachten een aanzienlijk bedrag. Vanuit het oogpunt van voedselveiligheid is het van belang te weten hoe de karkassen verder worden verwerkt. Als de karkassen worden verhit tijdens de productie van de varkensvleesproducten worden de eventueel aanwezige bacteriën onschadelijk gemaakt. Daarom zouden er verschillende Maximaal Geaccepteerde Prevalentie (zogenaamde MAP) niveaus kunnen worden gedefinieerd voor groepen karkassen met een verschillend verwerkingsproces (hoofdstuk 5). Groepen karkassen die voor vers vlees worden gebruikt, zouden een lager MAP niveau mogen hebben dan groepen karkassen voor verhitte vleesproducten. De opbrengsten voor karkassen die voor vers vleesproducten geschikt zijn, worden hoger gesteld dan de opbrengsten voor karkassen voor verhitte producten. Op deze manier worden er verschillende segmenten gevormd, zoals het vers vleessegment en het bewerkt vleessegment. Het systeem van segmentatie is een veelbelovende aanpak om de voedselveiligheid van varkensvleesproducten te verbeteren.

In hoofdstuk 5 is eveneens gekeken welk type beheersmaatregelen het voordeligst zijn in het systeem met MAP niveaus. Er zijn vier typen onderscheiden: geen maatregelen (basis), preventieve maatregelen, correctieve maatregelen en alle maatregelen. Preventieve maatregelen worden continu uitgevoerd om te voorkomen dat *Salmonella* wordt geïntroduceerd of verspreid. Correctieve maatregelen worden tijdelijk geïmplementeerd wanneer de prevalentie van groepen varkens of karkassen te hoog wordt. Onder alle maatregelen wordt verstaan dat zowel de preventieve als de correctieve maatregelen worden toegepast. In dit geval zullen er minder vaak correctieve maatregelen genomen hoeven te worden omdat er al preventief wordt gewerkt aan een lage prevalentie. Uit de resultaten kwam naar voren dat preventieve maatregelen de voorkeur verdienen. De kosteneffectiviteit van het nemen van preventieve maatregelen is hoger dan van correctieve maatregelen.

5 Haalbaarheid van *Salmonella* beheersprogramma's

Met behulp van de theorie van Strategisch Management zijn de belangrijke onderdelen voor het ontwikkelen van een goed *Salmonella* beheersprogramma in de varkensvleesketen bepaald (hoofdstuk 6). Voor het ontwikkelen van een strategie of programma worden bij Strategisch Management vier stappen onderscheiden: formuleer een missie en doel, voer een interne analyse uit, voer een externe analyse uit en, tot slot, formuleer en selecteer mogelijke strategieën. In dit proefschrift zijn ter illustratie twee programma's geformuleerd voor de Nederlandse varkensvleesketen: een Voedselveiligheid-programma en een Concurrentie-programma. Het eerste programma richt zich volledig op voedselveiligheid en heeft als doel alle varkensvlees gerelateerde gevallen van menselijke salmonellose te voorkomen. Om aan te tonen dat de prevalentie van een kleine groep laag is, moeten veel monsters genomen worden. Omdat de kosten te hoog zijn, is een dergelijk programma momenteel niet haalbaar. De kosten voor het testen alleen zouden al bijna 3 Euro per varken bedragen. Het Concurrentie-programma heeft als doel om te kunnen blijven concurreren op de internationale markt. Hierbij is uitgegaan van het ontwikkelen van een programma dat geënt is op het programma van een belangrijke concurrent zoals Denemarken. Het nadeel van een dergelijk programma is dat de sterke punten en de mogelijkheden die typisch zijn voor de Nederlandse varkensvleesketen niet volledig benut worden.

Het is een uitdaging om een beheersprogramma te ontwikkelen waarin een goede balans tussen de kosten en het verbeteren van voedselveiligheid wordt gevonden. Het zou wenselijk zijn als de Europese Unie uniforme procedures en normen voorschrijft aan haar lidstaten waarin gebruik wordt gemaakt van een gevoeligere testmethode. Deze methode en normen zouden dan ook moeten gelden bij import uit landen buiten de Europese Unie.

6 Belangrijkste conclusies

Het onderzoek, zoals beschreven in dit proefschrift, heeft meer inzicht gegeven in de epidemiologische en economische effecten van verschillende beheersstrategieën om de voedselveiligheid van varkensvlees met betrekking tot *Salmonella* te verbeteren. De multidisciplinaire aanpak van het probleem, waarin epidemiologie, economie, veterinaire wetenschap en besluitvorming zijn samengevoegd, heeft zeker bijgedragen aan dit inzicht.

De volgende conclusies kunnen op basis van het onderzoek worden getrokken:

- Deskundigen hebben aangegeven dat bij het verbeteren van voedselveiligheid van varkensvlees met betrekking tot *Salmonella*, het verminderen van de verspreiding van de bacterie effectiever is dan het verminderen van de introductie van de bacterie in de keten.
- Het onderzoek heeft duidelijk aan het licht gebracht dat bij *Salmonella* beheersing een ketenaanpak beter is dan een aanpak per schakel. Indien een aanpak per schakel wordt gekozen, zou de wachtruimte de eerste schakel zijn om maatregelen te implementeren omdat daar de kosteneffectiviteit het hoogste was. Bij een ketenaanpak blijkt echter dat dit minder kosteneffectief is dan het implementeren van maatregelen in de slachterij en de vleesvarkenshouderij.
- Niet iedere beheersmaatregel in de keten leidt tot een verlaging van de prevalentie van met *Salmonella* gecontamineerde karkassen.
- Het implementeren van pakketten maatregelen in de vleesvarkenshouderij en slachterij kost ongeveer € 4,40 per varken. Veel van deze maatregelen zijn generiek en hebben mogelijk ook een reducerend effect op andere pathogenen in de keten. Daarom zouden deze kosten niet alleen moeten worden toegeschreven aan *Salmonella* beheersing.
- De effectiviteit van *Salmonella* beheersing hangt af van de inzet van alle participanten in een schakel. De relatie tussen het percentage participanten dat actief *Salmonella* beheersing implementeert en de uiteindelijke prevalentie van gecontamineerde karkassen is niet lineair. Met andere woorden, een klein deel van de participanten in een schakel kan een onevenredig groot negatief effect hebben op het uiteindelijke ketenresultaat.
- Indien alleen een maximum wordt gesteld aan de gemiddelde prevalentie van gecontamineerde karkassen op de lange termijn (bijv. een jaar), voorkomt dit niet dat er groepen karkassen met een veel hogere prevalentie richting consument gaan.
- Het nemen van preventieve maatregelen bij *Salmonella* beheersing is te verkiezen boven het nemen van correctieve maatregelen.
- Een uitbetalingssysteem gebaseerd op de prevalentie van afgeleverde karkassen is een veelbelovend systeem om de voedselveiligheid te verbeteren.
- Een ideaal *Salmonella* beheersprogramma bestaat niet, maar de principes van Strategisch Management bieden een gestructureerde basis bij het ontwikkelen van een beheersprogramma dat voldoet aan de doelstellingen. Het zou wenselijk zijn als er internationale uniforme richtlijnen voor testprocedures en normen gedefinieerd worden.

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Nawoord

Zo blij!! Het boekje is nu klaar. Als je aan iets nieuws begint, weet je vaak niet waar je 'ja' tegen hebt gezegd. Nadat ik 'ja' had gezegd tegen het promotieonderzoek, heb ik me de afgelopen jaren wel eens afgevraagd waarom ik dat gezegd had. Na mijn studie heb ik eerst gezocht naar een promotiebaan op het gebied van ethologie, maar toen Ruud Huirne in 1998 met een projectvoorstel kwam over ketenonderzoek leek me dat ook erg leuk. Omdat het voor het ketenaspect aantrekkelijk was een onderwerp te kiezen waar iedere schakel mee te maken heeft, schakels afhankelijk zijn van elkaar en waar iedere schakel afzonderlijk iets aan kan doen, hebben we voor Salmonella gekozen. Achteraf bleek dit een hele goede keuze, omdat het steeds actueler is geworden. Voedselveiligheid is boeiend en belangrijk, al denk ik dat de volgende stelling van Marjan den Ouden uit 1996 zeker nog van toepassing is: "Hoewel de Salmonella problematiek zeker niet onderschat mag worden, leven er vooralsnog meer mensen van dan er aan sterven".
Een onderzoek uitvoeren op gebieden waar je je tot dan toe nog niet in verdiept had, is soms lastig. Dat er nu toch een compleet proefschrift ligt, heb ik mede te danken aan vele mensen in mijn omgeving. Al deze mensen wil ik hiervoor heel hartelijk bedanken en een aantal van hen in het bijzonder. Allereerst mijn promotoren Ruud Huirne en Paul van Beek. Ruud, jouw enthousiasme is gedurende het hele traject een grote stimulans geweest. De snelheid waarmee ik de papers die ik je gestuurd heb, met goede opmerkingen weer terugkreeg, is uniek. Paul, jouw betrokkenheid en geloof in dit onderzoek hebben me vaak geholpen door te gaan. Jullie zijn de enige twee personen die bij het gehele onderzoekstraject betrokken zijn geweest en waren een rots in de soms woelige branding. De begeleidingsgroep heeft vele wisselingen gekend en de bijdrage van een ieder heb ik zeer op prijs gesteld. Twee personen wil ik graag met name noemen: Helmut Saatkamp en Gé Backus. Helmut, het onderwerp sprak je aan, de tijd ontbrak wel eens, toch ben je zeer terecht co-promotor. Jouw suggesties en opmerkingen hebben een waardevolle bijdrage geleverd aan de kwaliteit van de artikelen. Gé, jouw positieve en gedreven wijze van vertellen werkt aanstekelijk, dus toen jij samen met Ruud dit project aan mij voorstelde, kon het alleen een 'ja' worden. Bij de uitvoering van het onderzoek heeft Fred Vos een essentiële rol vervuld. Fred, het was geweldig om met jou het epidemiologische model op te zetten. Jouw kritische houding over wat er precies gemodelleerd moest worden en de gezellige samenwerking maakte deze periode tot de beste van het onderzoek. Verder bedank ik ook Anthonie Vonk Noordegraaf, Michiel van Boven en Christien Ondersteijn voor hun hulp bij de theoretische onderbouwing in delen van het onderzoek. En zonder de

financiële bijdrage van AKK, Nutreco en Nedap was dit onderzoek nooit tot stand gekomen.

De gezellige tijd op het werk heb ik te danken aan de collega's van zowel het Praktijkonderzoek als van ABE. Ik heb genoten van de uiteenlopende gesprekken tijdens de vele koppen (smaakjes)thee met Fred, Esther, Mirella en Tanya en de appelsessies met Paul. Ook heeft de vriendschap en interesse van vriend(inn)en mij veel goed gedaan in een periode waarin het werk niet altijd even leuk was. Een knuffel doet soms wonderen. In dit kader kan ik ook Quinta, Casper en Hobbes niet ongenoemd laten. En natuurlijk wil ik mijn ouders en familie, in het bijzonder mijn zus Anne Marie, bedanken voor hun onaantastbare vertrouwen. Tot slot zou deze serie van dankbetuigingen niet compleet zijn als ik Patrick niet zou noemen. Patrick, jouw liefde en steun betekenen onvoorstelbaar veel. Samen kunnen we alles aan en ook dat maakt me zo blij!!

Monique

Curriculum Vitae

Monique Antoinette van der Gaag werd op 9 juli 1972 geboren te Middelharnis. In 1991 behaalde zij haar VWO diploma aan de Rijksscholengemeenschap Goeree Overflakkee. In datzelfde jaar begon zij met de studie Zoötechniek aan de Landbouwuniversiteit Wageningen (nu Wageningen Universiteit). Tijdens de studie deed ze een afstudeervak Ethologie over fysiologische en ethologische effecten van morfine op biggen, een afstudeervak Voorlichtingskunde over verantwoord diergeneesmiddelengebruik en een stageopdracht over de favoriete leefomgeving van leguanen in Costa Rica. In 1996 studeerde zij af in de oriëntatie Veehouderij. In 1997 werkte ze tijdens de uitbraak van Klassieke Varkenspest in Nederland enkele maanden bij het Coördinatie Centrum Varkensopkoop om vervolgens in september 1997 in dienst te treden bij het Praktijkonderzoek Varkenshouderij (nu Praktijkonderzoek van de Animal Sciences Group). In 1998 is ze begonnen aan een promotieonderzoek dat werd uitgevoerd in samenwerking van de leerstoelgroep Agrarische Bedrijfseconomie van Wageningen Universiteit en resulteerde in dit proefschrift. Zij werkt momenteel bij het cluster Dierenwelzijn en Diergezondheid van het Praktijkonderzoek van de Animal Sciences Group van Wageningen UR.

Omslag

- Ontwerp : Annita van Betuw, Wageningen
- Foto : Praktijkonderzoek van de Animal Sciences Group

Drukker

- Grafisch Bedrijf Ponsen en Looijen, Wageningen

Financiering

Dit onderzoek is financieel mogelijk gemaakt door:

- Stichting Agro Keten Kennis, 's Hertogenbosch
- Nutreco, Boxmeer
- Nedap Agri, Groenlo
- Praktijkonderzoek van de Animal Sciences Group, Lelystad
- Leerstoelgroep Agrarische Bedrijfseconomie van Wageningen Universiteit