COST-EFFECTIVENESS OF

Echerichia coli O157:H7 CONTROL

IN THE BEEF CHAIN

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Bouda Vosough Ahmadi

COST-EFFECTIVENESS OF *Escherichia coli* O157:H7 CONTROL IN THE BEEF CHAIN

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Cost-effectiveness of *Escherichia coli* O157:H7 control in the beef chain

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To my parents, Farima and Ahmad
تقدیم به فریما و احمد

ABSTRACT

Beef is considered to be an important source of food-borne disorders caused by the bacteria *Escherichia coli* O157:H7 (VTEC O157). Through the beef-supply chain, this bacterium can pose a risk to public health. The objective of this research is to provide quantitative insight in the cost-effectiveness of interventions to control VTEC O157 at two levels of the Dutch beef-supply chain: dairy farms and industrial beef slaughterhouses. At the slaughterhouse level, seven decontamination measures were evaluated, namely hot-water wash, lactic-acid rinse, trimming, steam-vacuum, steam-pasteurization, hide-wash with ethanol and gamma irradiation. The effectiveness of the decontamination measures was estimated based on a stochastic epidemiological simulation model. The net costs of the decontamination measures were calculated with a deterministic economic model. To assess the effectiveness of on-farm interventions, a transmission model that mimics the dynamics of VTEC O157 bacteria in a typical Dutch dairy herd, was used. The evaluated on-farm interventions were vaccination, diet modification, probiotics (colicin) and additional hygiene. The net costs of the on-farm interventions were based on a deterministic economic model. The effectiveness of the on-farm interventions and slaughterhouse decontamination measures was expressed as the prevalence of contaminated carcass quarters. The baseline prevalence (i.e., without intervention) was estimated to be 4.3%. The net costs of implementing single decontamination methods at the slaughterhouse were calculated to be € 0.22 to € 0.65 per carcass quarter which is 16% to 40% of the net profit per carcass. The costs of combining decontamination methods at the slaughterhouse vary from € 0.44 to € 1.88 per carcass quarter and the costs of irradiation were estimated at € 4.65 per carcass quarter. The annual costs of implementing on-farm interventions for the supplying dairy farms were calculated to be € 1.75, € 2.25, € 18 and € 40 per carcass quarter for probiotics, vaccination, additional hygiene and diet modification respectively. It is concluded that: i) applying decontamination measures at the slaughterhouse level is more cost-effective than applying interventions at the farm level or at the chain level (i.e., both slaughterhouse and farm levels), ii) carcass trim and steam-pasteurization are the most cost-effective slaughterhouse interventions, and iii) vaccination and colicin supplementation have the best cost-effectiveness ratios of the on-farm interventions.

PREFACE

During two years of work as a veterinary practitioner (1998-2000), the importance of economics and management of animal diseases was clearly revealed for me. Very soon, I realized that in a country like Iran, with many endemic-contagious animal diseases and low level of bio-security measures, both on the farms and in the country borders, a basic knowledge on 'economics' would be an advantage for a veterinarian. However, there was not such a course in the list of the veterinary medicine program. It didn't take me that long to find the Website of Wageningen University on the internet as one of the few places in the world that someone could study 'Animal Health Economics'.

In September 2001, I started the master program of 'Agricultural Economics and Management' with specialization in animal health economics at Wageningen University in the Netherlands. Given absolutely no background in economics, I experienced very tough time to follow the courses in the beginning. However, after couple of months I could adapt myself to the new field of study and to the new educational atmosphere. I gradually became interested to write my M.Sc. thesis on veterinary epidemiology and economics. To find a research topic, I was introduced to the 'farm management group' by *Dr. Klaas Frankena*, who later became one of my supervisors. Having finished the maser thesis as a preliminary step for a bigger project, I expressed my strong interest to work on that as my PhD project. The research proposal was written done by my supervisor *Dr. Henk Hogeveen* based on the preliminary results of my M.Sc. thesis and was submitted to the Mansholt Graduate School of Social Sciences. The project was funded by Mansholt and on April 1st, 2003 I started the project. Now looking back at my pas four years, I realize that I have many achievements and I have gained several professional and social skills. I owe these to many great people that I try to appreciate them here with my words.

First of all I would like to thank my promoter *Prof. Ruud Huirne* for all his supports, encouragement and enthusiasm as well as his great leadership. Dear Ruud: it was a great honor for me to work on a project under your supervision. I extremely enjoyed and learned from your broad and holistic view, which is based on your extensive research and management experiences, as well as your positive and inspiring attitude toward new ideas. I appreciate the time and efforts that you spent on my PhD project. Despite of your very tight schedule, you never canceled even a single PhD meeting during my four years work. This was another simple but crucial lesson for me. Thank you so much.

I have to thank my daily supervisor and one of the co-promoters of my PhD project *Dr. Annet Velthuis*. Dear Annet: thank you so much for many basic but important things for a scientific researcher that you taught me. I sincerely appreciate your patience and efforts that

you spent on critically reviewing my developed models, written manuscripts and conference papers and presentations. You were always accessible and ready, even in the weekends or in your free days, to answer my questions and propose a way to deal with difficulties in my research. I do believe that without your strong support I could not be able to finish the project in time with a satisfactory result. I will never forget your friendship and kindness.

I am also deeply indebted to the other co-promoter of the project *Dr. Henk Hogeveen* for all the helps and encouragements he gave me during these years. Dear Henk: please accept my sincere thanks for both scientific and life lessons that I learned from you. You were always there to correct my way whenever I deviated from the track of the project. You taught me that it is possible to pass over small and big obstacles with the light of knowledge, wisdom and positive attitude. More than a supervisor, you have been a great friend of mine. We had several trips together that I never forget the good memories of them. My wife and I totally enjoyed the hospitality and kindness of you and your family being our host at your beautiful-cozy house. Henk, I have a deep and great respect to you being so devoted to your family despite of your heavy research and teaching activities. I wish you and you your family all the best.

I would like to appreciate my supervisor *Dr. Klaas Frankena* for all his helps and supports during implementing the 'farm level' phase of this project as well as writing the chapter 4. Dear Klaas: although we worked together for a very short time, but firstly it was a great honor for me to work with you and secondly it was truly beneficial for me to learn many things from you. I know you as a very smart, knowledgeable and expert in your professional field and very humble, kind and helpful person in you social life. I try to follow you as a good example in my life.

I would also like to thank the members of the supervision committee of my PhD projects namely: *Prof. A. Havelaar, Dr. A. Heuvelink, Drs. B. Ooms, Dr. B. Berends, Dr. P. de Ruyter, Dr. P. Vesseur and Dr. R. van Oosterum* for their willingness to participate in the annual meetings and for their expertise. The 'farm phase' of this project would not have been possible without the cooperation from the Department of Veterinary Clinical Science and Animal Husbandry of the University of Liverpool. Herewith, I would like to express my sincere thanks and respects to the former head of the group *Prof. N. French*, and to *Dr. R. Christley* and other colleagues in that group for giving me the opportunity for this cooperation. My deep and special thanks are to *Dr. J. Turner* who kindly provided me her developed model and taught me how to run and modify the model. Dear Jo: It was a great honour for me working with you. Please accept my appreciation for your warm hospitality and kind helps during my visits to Liverpool as well as all your supports during the implementing the project and writing and revising the paper. I would like to thank the following individuals who helped and supported me technically, scientifically or facilitated the process of finding data or arranging interviews: *Dr. M. Nauta, Dr. M.-J. Mangen, Dr. T. Roberts, Dr. M. Schouten, Dr. J. Dijkstra, Mr. C. van Hertem, Mr. F. Doper, Mr. van Roessel, Mrs. L. de Jong, Mr. K. Fremery, Mr. H. van.Laar and Mr. J. Goelema*.

During the last four years, I have had the pleasure to work in the Business Economics Group. I would like to thank the head of the group *Prof. Alfons Oude Lansink* as well as all my current and former wonderful collogues in this group that I truly enjoyed working and sharing the moments of life with them. Thank you all for being such close and supportive friends. My specific thanks are dedicated to our secretariats *Anne, Marian, Karin* and to our lovely technical specialist *Martin* for their sincere assistances during last four years. I am so thankful to Mansholt Graduate School of Social Sciences for their financial support as well as monitoring and supervising the progress of the project.

My brilliant office-mate and best friend *Ilya*: I was so lucky to share the office with you. I truly enjoyed talking to you and being inspired and motivated with your strong positive energy. Our friendship during last six years is full of happy and good memories that I never forget them. I wish you and *Olesya* the best in your future. I also would like to thank *Petra,* my recent office-mate, for warm conversations and exchange of ideas that we had. Wageningen is a unique place to meet interesting and intelligent people coming from all around the world. During my six year stay I had the honor to establish many friendly relationships with many of those individuals. I would like to express my warmest thanks and love to all my fiends, who I met them for the first time in Wageningen, for their kindness to me. Some are very special and they are always in my heart: *Catarina and Goncalo, Kamyar, Sina, Mazdak, Nazanin, Iman, Emad, Hassan, Akbar, Mohammad, Ilya, Rafat, Lusine, Szvetlana, Tanya, Irnina, Natasha* and *Victor*. Also my special thanks to all my fellow Iranian students in Wageningen for the time that we shared together being far away from homeland. I am very thankful to my dear aunt *Razijoon* and *Mr. Noori's* family for all their kindness and hospitality during my visits to their place in The Hague.

Last but not least, I should express my appreciation to my family and parents. I owe my life and whatever I have learned and obtain entirely to my parent. My deepest gratitude is to my mother and father. Thank you for all your sacrifices that you have done for me. I would like to thank my wonderful brother and sister. You have been always very close and supportive to me. Thank you so much. Finally, my sincere thanks to my wife for her passion, patience, optimism, helps and supports during these years. We have been far away from each other many times during last years, but so closed via our hearts. Without your patience and support I could never been able to finish my PhD program. Merci.

Bouda Vosough Ahmadi / April 2007 / Wageningen / The Netherlands

CONTENTS

Chapter 1

General Introduction

Vosough Ahmadi B.

1. INTRODUCTION

Food-borne diseases occur often in the human population. The causes of these diseases are often microbiological contaminations. Salmonellosis and campylobacteriosis are the most frequently reported food-borne zoonoses in human population in Europe, with 135,000 cases/year each (EU zoonoses report, 2003). Other pathogens are less frequently reported but have sever health consequences for the infected persons like some strains of *Escherichia coli* bacteria and *E. coli* O157:H7 in particular. *E. coli* O157:H7 belong to a group of bacteria known as enterohaemorrhagic *E. coli* (EHEC) that cause bloody diarrhea in human. This EHEC belongs to a larger group of bacteria called verocytotoxin-producing *E. coli* (VTEC). Many VTEC serotypes have been associated with human infections. The focus of this thesis is on *E. coli* O157:H7 that is potentially pathogenic for humans. We call it VTEC O157 in this thesis.

A human infection with VTEC O157 is associated with a wide range of symptoms, including non-bloody diarrhoea (i.e., gastroenteritis), bloody diarrhoea (i.e., hemorrhagic colitis), life-threatening complications such as hemolytic-uremic syndrome (HUS) particularly in children under five-year-old, thrombotic thrombocytopenic purpura (TTP) in elderly people, and death. Hemorrhagic colitis is the name of the acute disease caused by VTEC O157. The number of cases is not high, but this is probably not reflecting the true frequency. Victims most likely seek medical attention because of the unmistakable symptoms of profuse, visible blood in severe cases, but less severe cases are not seeking medical attention and are probably more numerous. All people are believed to be susceptible to hemorrhagic colitis, but young children younger than five and the elderly appear to progress to more serious symptoms more frequently. Up to 15% of the young hemorrhagic colitis victims may develop HUS, characterised by haemolytic anaemia, thrombocytopenia and acute kidney insufficiency. HUS cases can end up with end stage renal disease (ESRD), indicating irreversible failure of the renal function (Besser et al., 1999). In the elderly, HUS plus fever and neurological symptoms, constitutes TTP. This illness can have a mortality rate in the elderly as high as 30% in outbreaks (Todd and Dundas, 2001). Based on epidemiological surveys in the Netherlands, it is estimated that the incidence of VTEC O157 originated diseases is 1,300 (median) cases of gastroenteritis, 590 hemorrhagic colitis and 22 cases of HUS per year (Havelaar et al., 2004).

Since the first report of VTEC O157 as a human pathogen in 1982 (Phillips, 1999), it has been of concern to the public health authorities and countries such as USA, Canada, Japan, Scotland and UK have experienced several large outbreaks (Allison et al., 2000; Bell et al., 1994; Belongia et al., 1991; Chapman et al., 1993; Vogt and Dippold, 2005; Willshaw et al., 1994). In the latest food-borne human outbreak in United States, that was associated to consumption of contaminated fresh spinach, 183 infected cases with VTEC O157 were reported from 26 states (*E. coli* investigation team, 2006). Among the ill persons, 95 (52%) were hospitalized, 29 (16%) had HUS, and one person died.

In the Netherlands, the first HUS outbreak in four children was confirmed in 1996. The source of infection was most probably swimming water (Cransberg, 2006). In 1998, seven family members of a veal-calf farmer, including one of the parents and six children, were infected (Heuvelink et al., 1998). Two outbreaks in children happened in 1999 and 2002, after visiting their grandparents' farms at which infected cattle were identified later (Heuvelink, 2002). In 2000, a HUS case in a 1.5-year-old boy was traced back to visiting a petting zoo where some sheep and goat were infected with VTEC O157 (Heuvelink et al., 2000). In September 2005, the first national food-borne outbreak of VTEC O157 was reported (Doorduyn et al., 2006). A total of 21 laboratory-confirmed cases and another 11 probable cases were reported. Consumption of a raw beef product, steak tartar was identified as the source of the outbreak.

The concept of "disability adjusted life years" (DALY) is often used to quantify the burden of human infections and to compare this burden with the burden caused by other diseases. DALYs are the public health indicator and are the sum of years lost by permanent mortality and life years spent in illness, weighted for severity of illness, integrating different clinical manifestations of the infection (Havelaar et al., 2004). The burden of VTEC O157 infections at the whole population level in the Netherlands was estimated to be 110 DALYs per year (Kemmeren et al., 2006). Approximately 90% of the disease burden of this pathogen is associated with HUS (100 DALYs). This disease burden is lower than the estimated disease burden for Toxoplasmosis, Campylobacter, Salmonella, Norovirus, Listeria and Rotavirus with a burden of 2,400; 1,300; 670; 450; 390 and 370 DALYs respectively (Kemmeren et al., 2006). However, VTEC O157 has the highest disease burden at individual level (87 DALYs per 1000 cases) compared to other enteric food-borne pathogens such as Campylobacter, Salmonella, Norovitus and Rotavirus (with <20 DALYs per 1000 cases). Moreover, VTEC O157 is infective in very low doses, particularly in children. The probability of getting ill by ingesting a single cell can be as low as 0.5% (Nauta, 2001). Occurring HUS and death in children generates anxiety and negative perceptions within the society about the public health systems and effective policies. Therefore, sever economic and health impacts of infection at both individual and population level brings it to the list of pathogens in concern for the society.

Although VTEC O157 can be found in the faecal flora of a wide variety of animals, cattle and cattle farm environments are known as the most important reservoirs of this pathogen (Cobbold and Desmarchelier, 2000; Hancock et al., 2001). Transmission of VTEC

O157 to humans occurs via food with animal origin, fruit and vegetables, water, person-to person and animal-to-person contact and occupational exposure. Undercooked ground beef and steak tartar have been implicated in many of the documented VTEC O157 outbreaks (Allison et al., 2000; Belongia et al., 1991; Chapman and Ashton, 2003; Doorduyn et al., 2006; Willshaw et al., 1994). Thus, it is clear that the cattle sector plays an important role in VTEC O157 outbreaks. This pathogen can enter the beef-supply chain at multiple points and can cross-contaminate other products once present. It was showed that 1.1% (6 of 571 samples) of minced-beef products were contaminated with VTEC O157 in the Netherlands (Heuvelink et al., 1999). Furthermore, the result of a VTEC O157 risk-assessment study suggests that 0.3% of raw Dutch steak-tartar patties are contaminated with the bacteria (Nauta, 2001). These observations in addition to the first national food-borne VTEC O157-outbreak in 2005, due to steak tartar consumption, confirm that the Dutch beef and beef products can be contaminated with this pathogen. Beside the possible mortality and sever health burden, occurrence of such beef-borne outbreaks, negatively affect the image of the beef sector and can impose sever economic losses to the beef industry. As an example, the BSE crisis in 2001 has imposed about €100 million per year in Belgium, resulting from additional preventive and controlling measures as well as the new legislations (Velthuis et al., 2002).

Interventions that reduce the risk of beef-borne human outbreaks can be applied at pre-harvest level (i.e., on dairy farms level) and/or post-harvest level (i.e., at slaughterhouse, retailer or consumer levels) of the beef-supply chain. Pre-harvest or on-farm interventions are either pathogen specific (e.g., vaccination or probiotics against VTEC O157) or general (e.g., cleaning water and feed troughs). At the post-harvest or slaughterhouse level interventions are not pathogen-specific and include all the carcass and meat antimicrobial-decontamination methods (e.g., carcass hot-water wash or steam-pasteurization). Although it is not very clear which interventions at which level of the beef-supply chain are more efficient (Koohmaraie et al., 2005), there are some indications. A VTEC O157 farm-to-table risk assessment model of steak tartar in the Netherlands concluded that intervention at the farm or during slaughter is probably more efficient to reduce health risks, than intervention at the consumer stage (Nauta, 2001). Because the beef-production industry consists of many players, and because implementation of any new intervention is mostly costly, there is a tendency to want the primary producers (dairy farmers) to make sure that cattle are free of VTEC O157. However, still it is not known at which level of the chain (i.e., farm or slaughterhouse) implementing interventions is more cost-effective. Moreover, the costs of interventions to control VTEC O157 in relation to the profits, in terms of reducing the frequency of contaminated produced beef are still unclear. Consequently, it is possible that much effort is made to reduce the human risk at a certain level of the supply chain, while more profit would be gained if this effort was made at another level. Another problem is that the costs are made at a different level of the supply chain than the benefits of a decreased level of contamination of beef are gained. Maybe some levels of the beef-supply chain bear the costs, while the benefits will be taken by the society as a whole. This lack of knowledge will make it difficult to make good decisions on which interventions to apply in the supply chain to reduce risk of contaminated beef. Thus, an integrated epidemiological-economic framework is required to support the decision-making process. Cost-effectiveness analysis is one form of full economic evaluation where both costs and consequences of interventions are examined (Drummond, 1997). Net costs of implementing interventions can be relatively easy quantified using cost-calculation approaches such as partial budgeting. However, estimating the effectiveness of interventions to reduce beef contamination requires more efforts. The availability of epidemiological and technical data on the effectiveness of interventions is crucial to the cost-effectiveness analysis. In the case of VTEC O157-contaminated beef, the uncertainty involved with the available data makes the decision making even more difficult. So, to deal with these problems field studies are needed, but they are difficult to design, hard to apply and in most cases disruptive to the production process. An alternative approach to field studies is computer modeling. Constructing computer-simulation models is a promising and commonly used alternative approach to estimate the effectiveness of interventions. In addition to the effectiveness, determining the implementation costs of the interventions is crucial for the chain players. Cost-effectiveness analyses on interventions against VTEC O157 along the beef chain are scarce.

Investigation on the cost-effectiveness of possible intervention methods in dairy cattle farms (which are the starting point of the beef-supply chain) and the slaughterhouse level (which is the most important sites for introducing pathogens to the clean beef carcasses) is the main focus of this research.

2. RESEARCH ISSUE AND RESEARCH OBJECTIVES

The overall objective of this research was to provide quantitative insight into the effectiveness and costs incurred to the beef-supply chain due to the interventions in controlling VTEC O157. This objective was subdivided into two parts: interventions on dairy farms and interventions at industrial beef slaughterhouses. The following research questions have been formulated:

- What are the most cost-effective interventions to be applied at Dutch dairy farms?

- What is effectiveness of the on-farm interventions in reducing the prevalence of VTEC O157 infected lactating cows?
- What are the costs of the on-farm interventions, per farm and per cattle?

■ What are the most cost-effective beef-carcass decontamination methods to be applied in a Dutch industrial beef slaughter plant?

- What is the effectiveness of the selected decontamination methods, in terms of reducing the prevalence of contaminated beef carcasses quarters with bacteria and reducing the number of bacteria on the surface of contaminated beef carcasses quarters?
- What are the costs of applying decontamination methods per quarter of carcass, in an industrial slaughterhouse?

■ What are the implications for the beef-supply chain? At which level of the chain interventions are the most cost-effective?

We built quantitative models to get insight into the epidemiological and economic consequences of different interventions on dairy farms and in beef slaughterhouses to reduce the risk of VTEC O157 contamination of beef. In the next section we will present different steps of the research.

3. OUTLINE OF THE THESIS

A schematic outline of this thesis is illustrated in Figure 1.1. In Chapter 2 an epidemiological simulation model of VTEC O157 transmission in an industrial beef slaughterhouse is presented. This model was used to evaluate the effectiveness of selected beef-carcass decontamination methods. Furthermore, a modelling approach to translate the results of experimental microbiological studies that are expressed in log CFU reduction into probability model inputs for simulation models is presented as an appendix to this chapter.

In Chapter 3 a cost-effectiveness analysis for the selected beef-carcass decontamination methods at a Dutch industrial slaughterhouse is presented. This analysis was performed by using the outputs of a deterministic-economic model as well the results of the epidemiological simulation model as presented in chapter 2. Chapter 3 describes the details of the economic model, cost items of implementing each decontamination method, the results of the cost-effectiveness analysis along with the results of the least-cost frontier analysis.

In Chapter 4 an epidemiological transmission model is presented that was used to evaluate the effectiveness of on-farm interventions in reducing the prevalence of lactating cows infected with VTEC O157.

Chapter 5 addresses two issues: the cost calculations of the on-farm interventions and a comparison of the two levels of the chain (i.e., cattle farms and slaughterhouses) from the cost-effectiveness perspective. This chapter explains and discusses which interventions at which level of the chain is the most preferable form the chain point of view.

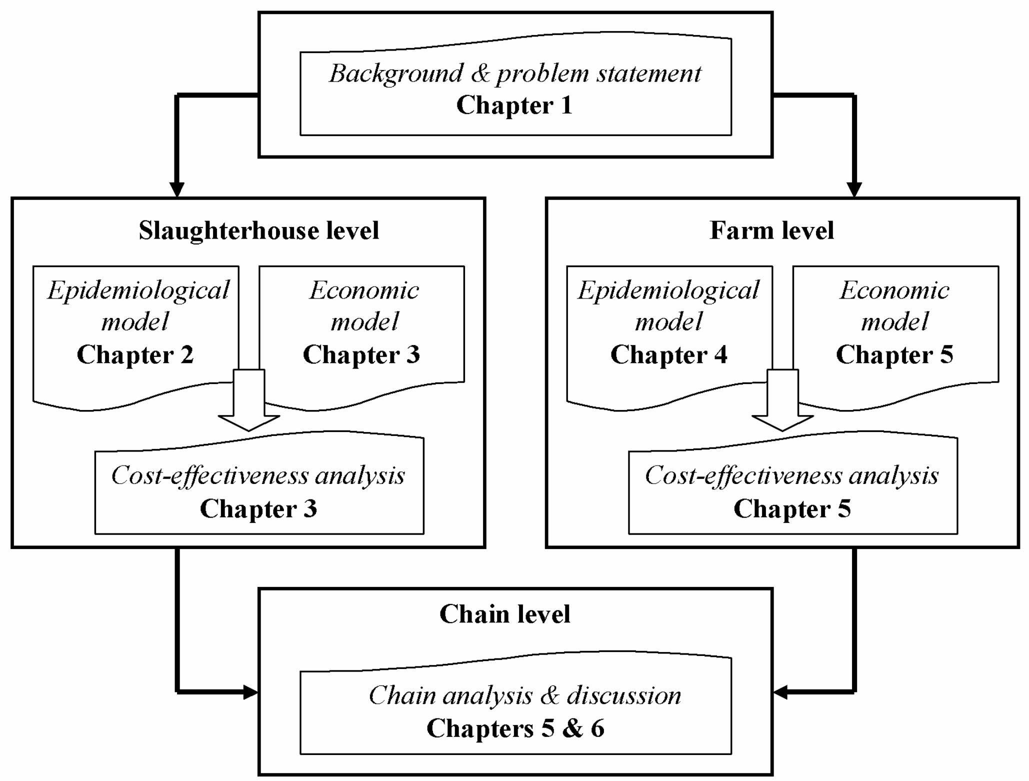

Figure 1.1. Outline of the thesis.

Chapter 6 presents a general discussion on: optimizing the beef-supply chain with respect to the interventions against VTEC O157, the issue of the beef import and export and its relation with the risk of VTEC O157, the effects of interventions on the public health and the implications for the VTEC O157 policy. A personal view on the ethics of food-safety and some suggestions for the future research finalizes this chapter and the thesis.

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Chapter 2

Simulating *Escherichia coli* O157:H7 transmission to assess effectiveness of interventions in Dutch dairy-beef slaughterhouses

Paper by Vosough Ahmadi B., Velthuis A.G.J., Hogeveen H., Huirne R.B.M. Published in Preventive Veterinary Medicine 77 (2006): 15-30.

SUMMARY

Beef contamination with *E. coli* O157:H7 (VTEC O157) is an important food-safety issue. To investigate the effectiveness of interventions against VTEC O157 in Dutch beef industrial slaughterhouses that slaughter 500 dairy cattle per day, a Monte Carlo simulation model was built. We examined seven carcass-decontamination methods, namely: hot-water wash, lactic-acid rinse, trim, steam-vacuum, steam-pasteurization, hide-wash with ethanol and gamma irradiation, and their combinations. The estimated daily prevalence of contaminated beef-carcass quarters as the output of the model was 9.2%. Contaminated was defined as containing one or more CFU on the surface of a carcass quarter at the end of the quartering stage. Single interventions (except irradiation) could reduce the prevalence to from between 6.2% to 1.7%, whereas the combination of interventions could lower it to from between 1.2% to 0.1%. The most powerful intervention was irradiation, which could reduce the prevalence to <0.1%. The results of this study indicate that application of single interventions might be useful, although not sufficient. Hence, a combination of interventions along the slaughter process is the more promising approach to reduce the prevalence of contaminated beef quarters.

1. INTRODUCTION

Since the first report of *Escherichia coli* O157:H7 (VTEC) as a human pathogen in 1982 (Phillips, 1999), it has been of concern to the beef-processing industry. In the Netherlands, an overall prevalence of 1.1% (6 of 571 samples) of VTEC-contaminated minced-beef products has been reported (Heuvelink et al., 1999). Furthermore, the result of a VTEC O157 risk-assessment study suggests that 0.3% of raw Dutch steak-tartar patties are contaminated with the bacteria (Nauta, 2001). The result of a recent study at the herd level suggests that 7.2% of Dutch dairy herds are infected with VTEC O157 (Schouten et al., 2004). In a study by Heuvelink et al. (2001) no VTEC O157 was isolated in the slaughterhouses, while >10% of carcasses were visibly contaminated with manure in 11 of the 27 slaughterhouses and >50% of the inspected carcasses were visibly contaminated with manure in six slaughterhouses. These facts imply that beef carcasses might become contaminated with VTEC O157 during the slaughter process in Dutch slaughterhouses.

A variety of interventions that can reduce carcass contamination with VTEC O157 during the slaughter process are available (Huffman, 2002; Juneja and Sofos, 2002). But decision makers must decide which interventions to apply. Cost-effectiveness analysis provides decision makers insight into both the costs and the effectiveness of interventions. One of the ways to perform a credible cost-effectiveness analysis is to build an integrated epidemiological-economic model. This paper describes the epidemiological model to determine the effectiveness of the different slaughterhouse interventions.

The effectiveness of different interventions has been investigated in several studies in a laboratory environment (Phebus et al., 1997; Juneja and Sofos, 2002; Retzlaff et al., 2004). In most such studies, the reduction in the number of colony-forming units (CFU) of VTEC O157 on the meat surface was determined (Phebus et al., 1997; Retzlaff et al., 2004). However, the effectiveness of interventions to reduce the proportion or prevalence of the contaminated end product of the beef slaughterhouse is unknown. To determine this, field studies are needed, but these are difficult to design, hard to apply and in most cases disruptive to the slaughter process. A modelling approach is therefore a good alternative.

Our objective was to present a Monte Carlo model that simulates the dynamics of VTEC O157 in a Dutch industrial beef slaughterhouse. Our aim was to rank the different intervention methods according to their effectiveness in reducing the frequency of VTEC O157-contaminated beef-carcass quarters at the end of the quartering stage.

2. MATERIAL AND METHODS

2.1 The slaughter process

We modelled a typical Dutch dairy-industrial slaughterhouse, with a capacity of 500 dairy cattle per day. Cattle are loaded onto transport trucks at the farms of origin, transported to the slaughterhouse and unloaded into the lairage. Animals are kept in the lairage before entering the slaughter line. The modelled slaughter process has nine stages (Figure 2.1): 1- lairage; 2- de-hiding; 3- evisceration; 4- splitting (producing half carcasses); 5- fat and tail removal; 6- trimming (for decontamination); 7- washing (for lower carcass temperature); 8- chilling; and 9- quartering (producing quarters). In this model, until S4 (splitting), the whole carcasses is used as basic unit. The output until this stage is the prevalence of infected carcasses (500 carcasses). At S4 the carcass is split into two half carcasses by a transverse cut. The basic unit from this stage on is the half-carcass (1,000 halves). At stage S9, each half-carcass is broken down into two quarters. From that moment the basic unit is a quarter (2,000 quarters). These fore- and hindquarters are considered the end product of our model.

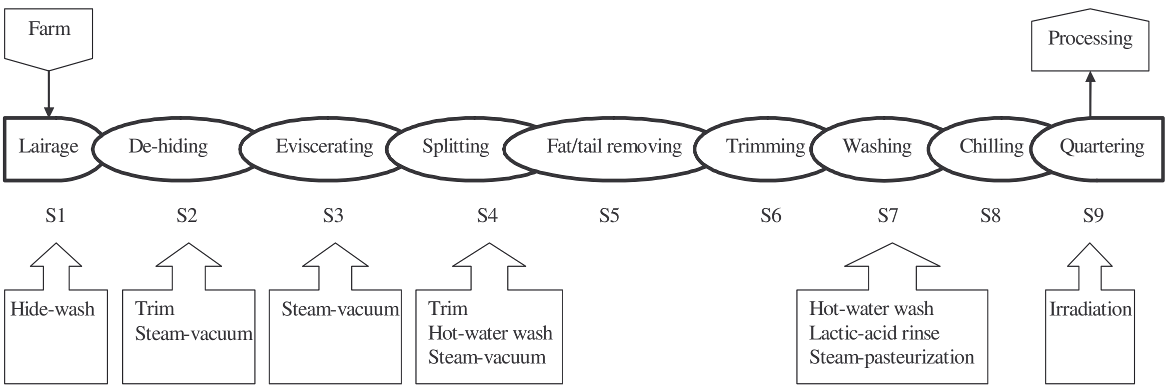

Figure 2.1. Schematic overview of the stages of the slaughter process and related interventions that can be used at each stage.

2.2 VTEC O157 sources and animal status

Most enteric pathogens (such as *Salmonella*, *Campylobacter* and VTEC O157) are most likely brought into the slaughterhouse by either the interior (gastrointestinal tract) or exterior (hide) of live animals or both (Small et al., 2002). The gastrointestinal (GI) tract is considered the main source of VTEC O157 beef contamination (Chapman et al., 1994). In this study GI-

positive (GI^+) refers to the animals that carry VTEC O157 in their GI tract and shed it in their faeces. Cattle that carry VTEC O157 on their hide (Sofos et al., 1999) are denoted as hide-positive (H^+). With respect to the bacterial sources mentioned, live cattle on the farm and at the slaughterhouse can be put into four categories: GI^+H^+; GI^+H^-; GI^-H^+; GI^-H^-.
When a GI^+ animal enters the slaughter process, it poses the risk of leaking faeces with VTEC O157 from the anus into the environment or onto the carcass. During the evisceration stage faeces can be leaked in the environment because of a rupture. On the other hand the contamination risk posed by an H^+ animal relates to the direct contact of the contaminated hide with the surface of the carcass, personnel, tools and surfaces in the slaughterhouse environment. This is mainly due to the large hide surface and its direct and frequent contact with personnel and tools (Bell, 1997; Hudson et al., 1998). In the following section the assumed transmission dynamics are described in detail.

2.3. Model structure

The model described in this paper was built using Microsoft Excel with @Risk add-in software (Palisade, 2002). Monte Carlo simulation was used to compute the average number of VTEC O157-contaminated carcass quarters per day. In the Netherlands, culled dairy cattle are the main source of beef. The slaughter cows each have a specific GI and H status, and are from many different herds (each with a different VTEC O157 prevalence). Therefore, the process of entering the slaughter line is assumed to be binomial for each animal. One iteration of the model represents one slaughter day, on which 500 cows enter the slaughterhouse. Quarters contaminated with no bacteria (zero CFU) are defined as negative (i.e. not-contaminated; N) and quarters with at least one CFU on their surface are defined as positive (i.e. contaminated; P). Within each stage of the slaughter process modelled, the status of a carcass can change from P to N, or the other way around. Therefore, the binomial distribution was also used as the basic stochastic process of the model (Vose, 2000). This stochastic process is outlined in Figure 2.2.

Two contamination routes and one decontamination route (Figure 2.2) per stage determine the contamination status of a quarter in each of the nine stages of the slaughter process (Figure 2.1). Corresponding to these routes three probabilities can be recognized. The first one is the probability of transferring VTEC O157 onto the carcass by means of the main risk factor of that specific stage (*Pr*). Examples of these probabilities are the probability of GI rupture during the eviscerating operation, and the probability of getting infected by the contaminated splitter saw during the splitting stage. The second probability is the probability of transferring the bacteria from the environment onto the carcass (*Pe*). This probability depends on the risk profile of the slaughterhouse and we assumed that this probability is equal for all stages. Because this probability is unknown for a typical Dutch dairy slaughterhouse, we assumed the same probability (1%) as used in a model about the spread of *Salmonella* in a typical Dutch pig slaughterhouse (Van der Gaag et al., 2004) . The third probability is the probability of eliminating the bacteria from the carcass (*Pd*) by a decontamination intervention.

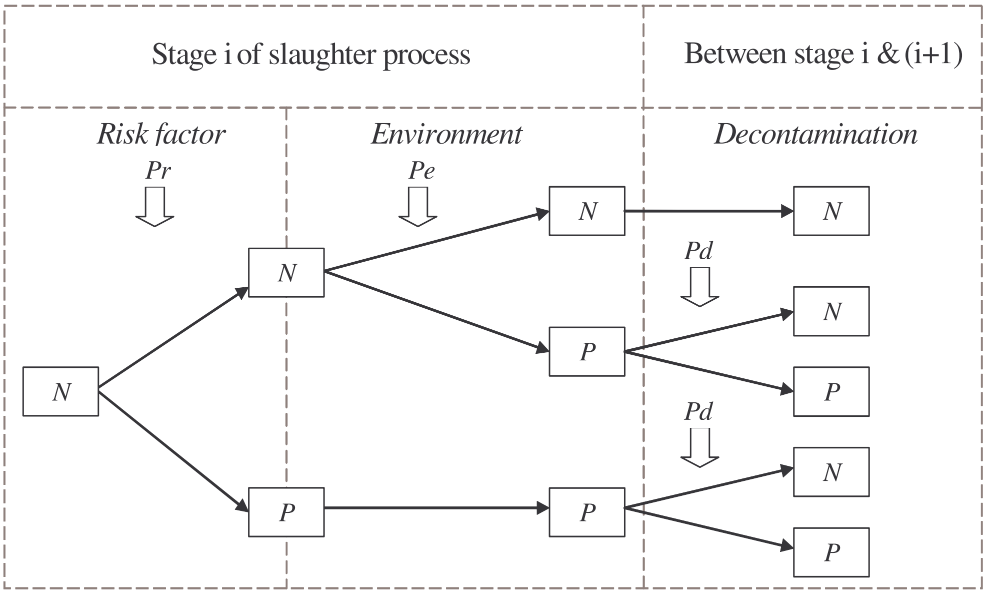

Figure 2.2. Contamination and decontamination processes modelled in each stage of the slaughter process. *N*: negative quarters, *P*: positive quarters (i.e. CFU>0), *Pr*: probability of bacterial transmission by the main risk factor of each individual stage, *Pe*: probability of bacterial transmission by the environment of each stage and *Pd*: elimination probability by decontamination methods after each stage.

The three routes are modelled as follows. Let *T* denote the total number of quarters entering a certain stage, $S_{(j)}^{+}$ the number of positive quarters after modelling the stochastic process *j*, where $(j=r)$ denotes the main risk factor, $(j=e)$ the environment and $(j=d)$ the decontamination process. $S_{(j)}^{-}$ is the number of negative quarters after each stochastic process. $S_{(0)}^{+}$ denotes the contaminated quarters coming from a previous stage. *Pr* and *Pe* are the probabilities of changing the status of a quarter from negative to positive due to the risk factors and/or environment, and *Pd* is the probability of change of status from positive to negative (i.e. elimination of bacteria) by decontamination. The three stochastic processes per stage in the slaughterhouse are then written as the following equations:

Contamination due to the *risk factor*

$$S_{(r)}^{+} = Binomial\left(S_{(0)}^{-};\Pr\right) + S_{(0)}^{+} \quad (1a)$$

$$S_{(r)}^{-} = T - S_{(r)}^{+} \quad (1b)$$

Contamination by the *environment*

$$S_{(e)}^{+} = Binomial\left(S_{(r)}^{-};Pe\right) + S_{(r)}^{+} \quad (2a)$$

$$S_{(e)}^{-} = T - S_{(e)}^{+} \quad (2b)$$

Decontamination

$$S_{(d)}^{-} = Binomial\left(S_{(e)}^{+};Pd\right) + S_{(e)}^{-} \quad (3a)$$

$$S_{(d)}^{+} = T - S_{(d)}^{-} \quad (3b)$$

In practice, environmental risks might come before the risk factors of each stage or vice-versa. In this model we simplified the process by separating the process into three parts following each other in a fixed order: contamination by a risk factor, contamination by the environment and decontamination.

2.4 Input data and distributions

2.4.1 Prevalence of VTEC O157-contaminated cattle

Table 2.1 summarizes the input data, distributions and the source of the data that are used in the model. Both the herd-level prevalence and animal-level prevalence are needed to simulate the number of GI^+ or H^+ animals entering the slaughterhouse. The number of GI^+ animals is simulated based on the herd and animal-level prevalence at negative-tested (i.e. assumed by us to be false-negative) and positive-tested herds (Nauta 2001). If P denotes probability of being infected, HP herd-level prevalence, AP^+ animal-level prevalence in positive-tested herds and AP^- animal-level prevalence in negative-tested herds, the probability of a positive animal entering the slaughterhouse was calculated as: $P = HP \cdot AP^+ + (1 - HP) \cdot AP^-$.

In the Netherlands herd-level prevalence is 7.2% (90%CI: 5.6–8.8) (Schouten et al., 2004). We considered a beta distribution for herd-level prevalence to take care of the uncertainty. The animal-level prevalence of GI^+ cattle coming from positive-tested herds was modelled using a uniform distribution with values between minimum 0.8% and maximum 22% due to the seasonal effect and sensitivity of the tests used (Heuvelink et al., 1998). The animal-level prevalence for the negative-tested herds is included as a constant value that was reported as 0.45% (Heuvelink et al., 1998) indicating that these herds might be false negative.

Table 2.1. Description of variables used in the model to estimate the VTEC O157 contamination in Dutch industrial beef slaughterhouses.

Variable	Distribution	Values/Formulas	Source
Animal-level prevalence on positive-tested herds	Uniform	Minimum: 0.8% Maximum: 22.4%	Heuvelink (2001)
Animal-level prevalence on negative-tested herds	Constant	0.45%	Heuvelink (1998)
Concentration of bacteria (log CFU) in 1 g of manure	Cumulative [a]	Minimum: 0 Maximum: 6 {x_i: 2, 3, 4, 5} {p_i: 0.46, 0.53, 0.87, 0.96}	Nauta (2001), Vose (2000)
Elimination probability	Poisson [b]	X: 0 (# of CFU) λ: expected number of CFU on quarters	Expertise of authors
Herd-level prevalence	Beta	α: 50, β: 628	Schouten (2004)
Gram of manure on each carcass	Beta [c]	Max: 10.1 α: 0.395, β: 2.47	Nauta (2001)
Hide-level prevalence in lairage	Triangular [d]	Minimum: 6.7% Mode: 32.9% Maximum: 42.3%	Avery (2002)
Probability of GI rupture *(Pr)*	Constant	1%	Ebel (2004)
Probability of infection via splitter saw *(Pr)*	Constant	1%	Expertise of authors
Probability of infection via environment *(Pe)*	Constant	1%	Van der Gaag (2004)
Slaughtered animals/day	Constant	500	Expertise of authors
Total surface of a carcass (cm^2)	Constant	32,000	Ebel (2004)
UK Animal-level prevalence	Constant	14%	Mechie (1997)

[a] Function: Cumulative(Min, Max, { xi },{ pi })
[b] Excel function: Poisson(x,λ, false)
[c] @Risk function: Max * RiskBeta(α, β)
[d] We scaled hide-level prevalence to reflect the GI prevalence of Dutch cattle

Because of the short period between the transport of animals and moment of slaughter, any change in prevalence of GI^+ animals is ignored. However, grouping animals in the transportation loads and the lairage before slaughter might increase the hide-level prevalence in animals (Small et al., 2002). No Dutch data on hide-level prevalence are available.

Therefore, we used a triangular distribution of hide-level prevalence with a minimum of 6.7%, a most-likely value of 32.9% and a maximum of 42.3%, based on sampling at the lairage stage in the UK (Avery et al., 2002). Using a UK animal-level prevalence (AP_{UK}) of 14% (Mechie et al., 1997), the hide-level prevalence (HP) was scaled to the Dutch situation: $HP_{Dutch} = (AP_{Dutch} \cdot HP_{UK}) / AP_{UK}$. Table 2.1 summarizes the input data used in this model.

2.4.2 Interventions

Various hygienic and decontamination measures can be applied along the whole slaughter process. Antimicrobial interventions can reduce the number of bacteria on the carcass surface, and in the case of elimination of all bacteria they can change the contamination status of the quarter (Smulders and Greer, 1998). In this study we considered the seven well known decontamination methods in the beef industry: hot-water wash (W); trim (T); steam-vacuum (V); steam-pasteurization (S); lactic-acid rinse (L); irradiation (Ir) and hide-wash with ethanol (H). We compared their effectiveness used individually or in combination. In general, applying carcass-decontamination technologies after the most contaminating stages (e.g. de-hiding, evisceration and splitting) seems the most logical. To choose the place of the interventions and the combination of interventions in the slaughter line in this study we followed three guidelines: 1- the place of the interventions suggested by the reference study (Phebus et al., 1997); 2- the place of the interventions based on practices of US beef-slaughter plants (Ebel et al., 2004); and 3- our own experience in slaughter practice and the technical feasibility of applying the interventions. As an example, hot-water wash is technically feasible almost at all stages (except in the chilling room). However it is usually done after splitting. On the other hand in Dutch beef-slaughter plants there is a washing stage (S7) for the pre-chilling purpose. Therefore hot-water wash was examined at both stages. Irradiation comes at the quartering stage, after carcasses come out of the chilling room and before entering the de-boning and processing stage. Irradiating the meat before the quartering stage is not logical because before this stage there are some highly contaminating stages that can re-contaminate the irradiated meat.

The combinations of interventions were chosen in such a way as to be consistent with the combinations that were mentioned in the reference study (Phebus et al., 1997), and those are combinations that are technically more justifiable. In that study there are some technical reasons (like more bactericidal effects) for choosing these particular combinations.

2.4.3 Simulation of elimination probabilities

The elimination probability *(Pd)* for each intervention was calculated based on results of experimental studies that are expressed as reduction in logCFU/cm^2 of the initial bacterial population. Because the number of CFU on each quarter follows a Poisson distribution, the probability of having zero CFU (i.e. *Pd*) was calculated from the expected number of CFU on a quarter after applying the intervention (λ). λ equals the initial number of CFU on each quarter minus the reported reduction due to a specific intervention (Phebus et al., 1997). The initial number of bacteria (CFU) on each quarter was simulated by multiplying two distributions: the amount of manure (in grams) transferred to the carcass (beta distribution) and the concentration of VTEC O157 in one gram of manure (cumulative distribution). The data and distributions used were based on a VTEC O157 risk-assessment (Table 2.1, Nauta, 2001). A beta distribution to describe the carcass contamination with manure was chosen after fitting the results of expert estimates to a series of probability distributions (Nauta, 2001). The parameters α and β express the level of carcass contamination with manure and its variability per carcass. A cumulative distribution was used to include the uncertainty related to the concentration of VTEC O157 in a gram of manure, based on data reported by Zhao (1995). For these simulations we assumed that each carcass has a total surface of 32,000 cm^2 and that each quarter receives equally one fourth of the total faeces. The mean elimination probabilities were based on 10,000 iterations. The last column of Table 2.2 represents these probabilities. For example, steam-pasteurization can reduce the initial number of bacteria by 3.53 logCFU/cm^2. Given our assumptions, this corresponds to an 83% probability of eliminating all the bacteria from a quarter.

Table 2.2. Reduction of VTEC O157 population from the surface of beef quarters and corresponding elimination probabilities of all CFU counts from carcass quarters

Intervention	Reduction (logCFU/cm^2)		Reference	Estimated elimination probability % *(Pd)*
	Mean	SE		
Hot-water wash (W)	0.75	0.49	Phebus et al. (1997)	34.69
Lactic-acid (L)	2.70	0.49	Phebus et al. (1997)	68.75
Steam-vacuum (V)	3.11	0.49	Phebus et al. (1997)	76.01
Trimming (T)	3.10	0.49	Phebus et al. (1997)	75.83
Hide-wash with ethanol (H)	5.00	0.20	Mies et al. (2004)	83.33
Steam-pasteurization (S)	3.53	0.49	Phebus et al. (1997)	83.17
Irradiation (Ir)	6.00	0.49 [a]	Molins et al. (2001)	99.48

[a] We assumed the same standard error as the other interventions.

2.5 Sensitivity analysis

Running the model using default input values and without incorporating the interventions was considered the baseline scenario. In the sensitivity analysis, the baseline output, was compared with alternatives (Vose, 2000). We changed only one of the input variables at a time. For the input variables that were described by distributions, such as herd-, animal- and hide-level prevalences, we examined the situations where these distributions shifted upwards or downwards by 50% of their mean in the default situation. In our view ±50% for the mentioned parameters generate such variations in the outputs that can demonstrate the most sensitive inputs of the model. Theoretically we can assume a reduction to zero or a large increase (e.g. 100%) in the value of a probability which in our opinion in this particular case (i.e. VTEC O157) is not fully compatible with the real observations. The number of iterations for the sensitivity analysis was 10,000. For the three input parameters for which the input was a single value namely the probability of contaminating the carcass with the splitter saw, due to a rupture or by the environment (in the basic situation all with a value of 1%), a probability of 0.1% and 10% were examined. We think that this range is compatible with natural variations for these values. We also believe that it is unlikely to have > and < of 10-fold change for the mentioned parameters. Finally, a sensitivity analysis was performed to study the effect of different effectiveness of the six single interventions using the standard errors of their CFU reduction.

For each scenario, the model was for the basic initial contamination and for a worst-case scenario. In the worst-case scenario the initial number of CFU was considered to be 13,487, while this value was 20 in the basic situation. For each simulation, 10,000 iterations were used, to have <1% change in the distribution statistics of the output variable.

3. RESULTS AND DISCUSSION

The baseline scenario represents the current slaughterhouse situation where no extra interventions are applied. The results of the baseline and different scenarios are shown in Table 2.3. In the baseline scenario, 9.2% of the daily produced beef quarters are predicted to be contaminated by VTEC O157 bacteria. The number of bacteria lies mostly between one and 20 per carcass quarter. When considering the maximum initial number of bacteria on the surface of the carcasses (i.e. the worst-case scenario), in the basic situation, the bacteria are never eliminated completely from the surface and in this case 34% of the quarters are contaminated (by 1 to 13,487 CFU per quarter) at the end of the slaughter line.

The single decontamination interventions W, L, T, V and H reduced the baseline prevalence from 9.2% to respectively 6.2%, 3.0%, 2.4%, 2.4% and 2.00%. In the reference study (Phebus et al., 1997) it is mentioned that trimming is more effective in experimental studies than in practice. This is also applies to steam-vacuuming. The reason for this is that in an experimental study, the site of contamination is known to the worker. Moreover trimming and steam-vacuum are focused on the visible contaminations and therefore their effect is not uniform on the whole surface. This has not been considered in our model, so their effectiveness is probably overestimated. The high effectiveness of hide-wash with ethanol confirms the importance of hide-level prevalence and interventions at this level. However, from the animal-welfare point of view, washing the hides of live animals with ethanol is debatable practice (Mies et al., 2004). Two combined interventions; WT (hot-water wash + trim) and WV (hot-water wash + steam-vacuum), have the same effect (1.8%). Carcass steam-pasteurization is more effective (1.7%) than the combined sets mentioned.

The sets of interventions consisting of two to four decontamination measures (also known as “hurdle strategy” (Juneja and Sofos, 2002), could reduce the baseline prevalence to 1.2% and 0.1%. These are applied over the whole slaughter process, so that some major changes in the slaughter process are necessary to apply them, which might not be desirable from an economic point of view. The effectiveness of combined interventions is not additive, as the experimental microbiological studies confirm.

Two intervention strategies, irradiation and WLVHS (hot-water wash, acid-lactic rinse, steam-vacuum, hide-wash with ethanol and steam-pasteurization) were predicted to reduce the baseline initial prevalence to 0.02%. Even at the highest level of the initial number of CFU (worst-case scenario), irradiation remains the only single decontamination measure that can eliminate almost all the bacterial population and reduce the prevalence. Irradiation cannot be applied in the middle of the process, because then the meat could be newly contaminated through the environment and the risky events of the other stages. Irradiation is recognized as a safe technology for destroying pathogens on the surface of beef (Molins et al., 2001) and is used in the US and elsewhere, though at the time of this study its application to beef (in the EU) is prohibited (EU, 2003). Application of the WLVHS strategy is as powerful as irradiation at the end of the process (ranking 2 in Table 2.3). The decision whether to invest in more interventions along the slaughter process or in a single intervention at the end of the line is for decision makers.

Under the worst-case scenario, almost all the interventions except a combined set of interventions (i.e. WLVHS) and irradiation were predicted to fail to eliminate all the VTEC O157 bacteria from the surface of the quarters. Carcass steam-pasteurization could slightly reduce the prevalence from 34% to 33.4% and its combinations with other methods fail to reduce the prevalence further.

Table 2.3. Predicted prevalence of VTEC O157-contaminated dairy-beef quarters in Dutch slaughterhouses.

Interventions	Slaughter stage(s)[a]	Baseline assumption for initial CFU counts/quarter[b]			Worst-case assumption for initial CFU counts/quarter[c]		
		Predicted quarter-level prevalence (%)		Predicted most-likely CFU counts	Predicted quarter-level prevalence (%)		Predicted most-likely CFU counts
		Mean	5th, 95th percentiles		Mean	5th, 95th percentiles	
None (baseline scenario)		9.2	4.4, 13.1	20	34.0	29.8, 39.6	13,487
Carcass hot-water wash (W)	S4	6.2	2.9, 9.0	4	34.0	29.8, 39.6	2,398
Carcass hot-water wash (W)	S7	6.1	2.8, 8.8	4	34.0	29.8, 39.6	2,398
Carcass lactic-acid rinse (L)	S7	3.0	1.4, 4.4	1	34.0	29.8, 39.6	27
Carcass steam-vacuum (V)	S3	2.7	1.2, 4.1	1	34.0	29.8, 39.6	10
Carcass trim (T)	S2	2.5	1.1, 3.8	1	34.0	29.8, 39.6	11
Carcass trim (T)	S4	2.4	1.1, 3.6	1	34.0	29.8, 39.6	11
Carcass steam-vacuum (V)	S4	2.4	1.1, 3.6	1	34.0	29.8, 39.6	10
Hide-wash with ethanol (H)	S1	2.0	0.9, 3.1	1	34.0	29.8, 39.6	4
WT	S4, S3	1.8	0.8, 2.8	1	34.0	29.8, 39.6	1
WV	S4, S3	1.8	0.8, 2.9	1	34.0	29.8, 39.6	1
Carcass steam-pasteurization (S)	S7	1.7	0.7, 2.5	1	33.4	29.3, 37.6	4
WS	S3, S7	1.2	0.5, 1.9	1	33.4	29.3, 37.6	1
WTS	S4, S3, S7	0.3	0.1, 0.6	1	33.4	29.3, 37.6	2
WVS	S4, S3, S7	0.3	0.1, 0.6	1	33.4	29.3, 37.6	1
WLTS	S3, S4, S2, S7	0.1	0.0, 0.3	1	33.4	29.3, 37.6	1
WLVS	S3, S4, S2, S7	0.1	0.0, 0.3	1	33.4	29.3, 37.6	1
WLVHS	S3, S4, S2, S1, S7	0.02	0.0, 0.1	1	00.8	00.5, 01.2	1
Irradiation of quarters (Ir)	S9	0.02	0.0, 0.1	1	00.8	00.5, 01.2	1

The results are ordered according to the mean prevalence of contaminated quarters

[a] Stages S1 to S9 correspond to slaughter stages illustrated in Figure 2.1.

[b] Assuming an initial CFU count of 20 per quarter (most-likely value).

[c] Assuming an initial CFU count of 13,487 per quarter (based on maximum values).

These results imply that in the case of having very high initial concentration of bacteria on the carcasses worst-case scenario (e.g. >log 5), the elimination probability could be zero or close to zero even if a powerful decontamination method is applied. This means that interventions will have no effect on the reduction of the prevalence of contaminated carcasses. However in the worst-case scenario the interventions mentioned can effectively reduce the number of CFU from the surface of the quarters (Table 2.3).

3.1 Results of the sensitivity analysis

Hide-level prevalence has a great influence on the number of the contaminated beef-carcass quarters (Figure 2.3).

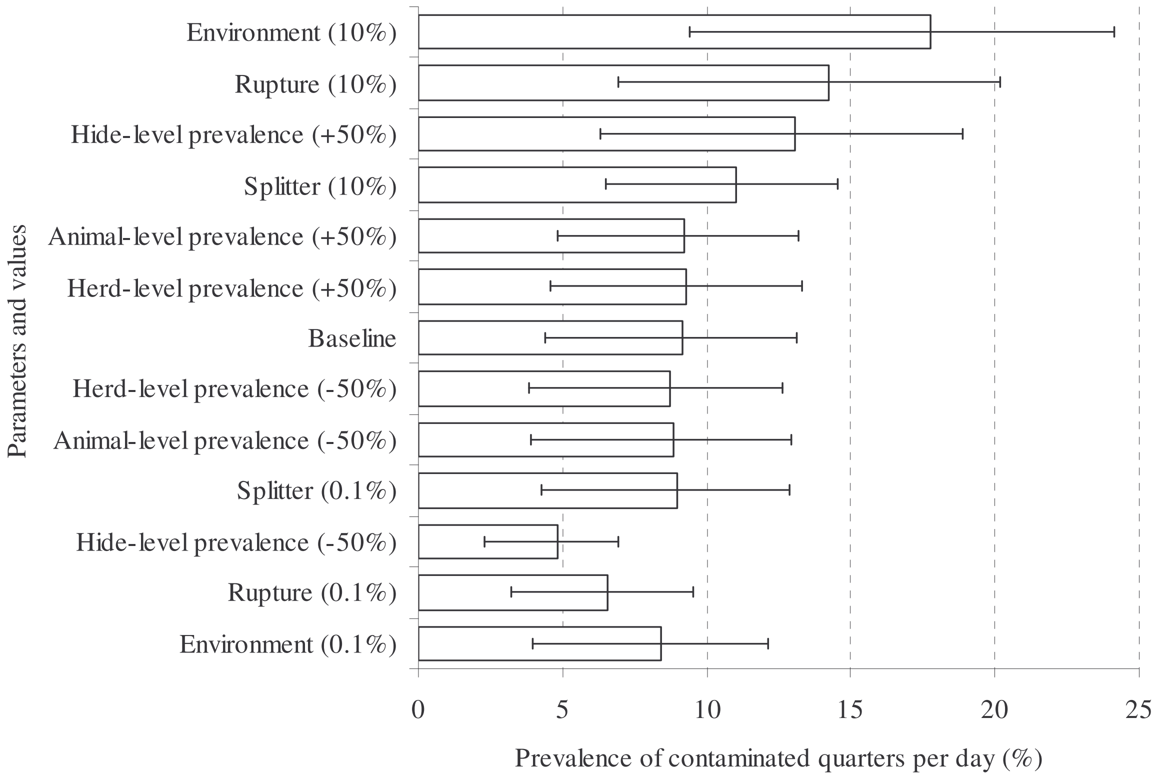

Figure 2.3. Results of the sensitivity analysis of the impact of six single input parameters of the model. Given are the mean prevalence and the 5th and 95th percentiles (error bars). For herd-, animal- and hide-level prevalences the + 50% of the default input values were examined, while for environment, GI rupture and splitter saw a minimum value of 0.1% and maximum value of 10% were examined.

Although the importance of hide contamination has been emphasized in previous studies (Avery et al., 2002; Bosilevac et al., 2004), we were surprised at such a strong influence. A reason for this effect might be the high value of the hide-level prevalence in the UK data used as input (Avery et al., 2002), despite the scaling we performed to adjust the data to the Dutch situation. However, an even-higher hide-level prevalence of 76% for animals entering the slaughterhouse has been recently reported from the US (Arthur et al., 2004). An implication of this could be that more attention should be paid to reduce the hide-level prevalence in the pre-slaughter stage to protect beef products against VTEC O157 contamination.

The output is also sensitive to the internal environment of the slaughterhouse. Increasing the probability of transmission from the environment leads to a large increase in output prevalence but decreasing it leads to only a small decrease in the number of contaminated quarters. Thus the current hygienic measures within slaughterhouses should be at least maintained. In general, hardly any field data for estimating the probabilities for the environment, gut rupture and splitter saw contaminations are available. Because the model output is sensitive to these parameters, more field data will be very helpful in improving the results of our model.

The result of a comparison of the effectiveness of six decontamination methods is illustrated in Figure 2.4. For these sensitivity analyses, the limits we used for the new runs were based on the mean ± 1 SE of the predicted mean of the baseline scenario. These results show that considering the uncertainty of the effectiveness of interventions, particularly of steam-pasteurization, steam-vacuum, trim and lactic-acid rinse, should influence our judgement. However, considering uncertainty does not affect the outcome of our analysis of hot-water wash and irradiation.

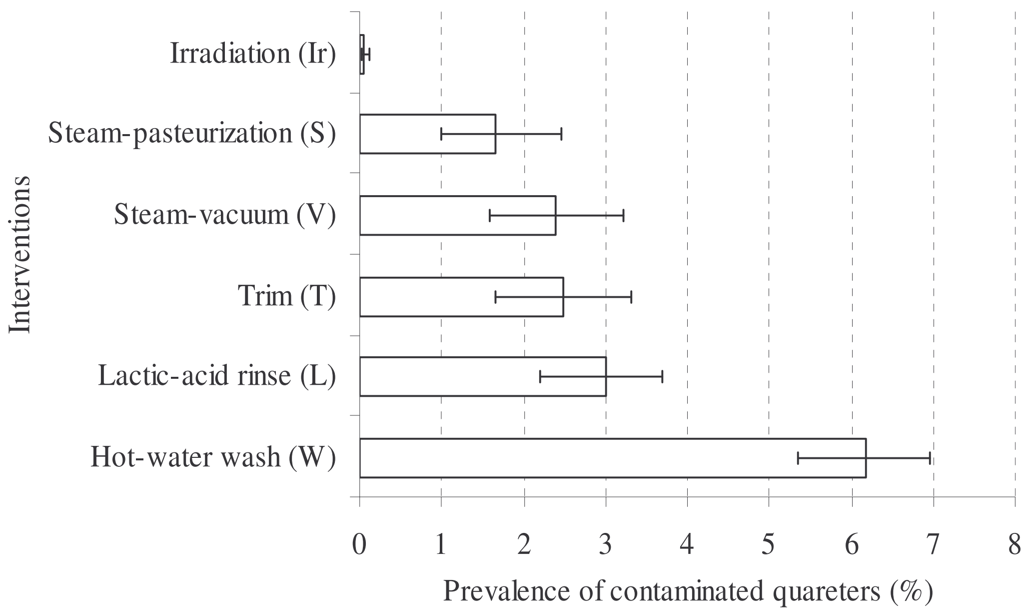

Figure 2.4. Predicted quarter-level prevalence and 5th and 95th percentiles (error bars), using default input values ± 1 SE for six decontamination methods (default values were based on the mean and SE of logCFU/cm^2 reduction reported in the reference studies).

3.2 Precision of detection

Baseline scenario (Table 2.3) shows 9.2% of the 2,000 daily produced beef quarters are contaminated mostly with one up to around 20 VTEC O157 bacteria. This is in contrast to measurements done in slaughterhouses in the Netherlands. In a study by Heuvelink et al. (2001) no VTEC O157 was isolated, even thought >10% of carcasses were visibly contaminated with faeces (in 11 of the 27 slaughterhouses). In six out of the 11 slaughterhouses, >50% of inspected carcasses were visibly contaminated. Other Dutch measurements confirm VTEC O157 contamination at the retail stage from 0.5% for minced mixed beef and pork, to 1.1% for raw minced beef (Heuvelink et al., 1999). This inconsistency can be explained by the fact that the model estimates the true prevalence, while in epidemiological studies the apparent prevalence is estimated. In the simulation model a carcass is positive if it is contaminated with at least one bacterium, whereas in practice, the detection limit of the test limits the number of positive carcasses found. There are many factors, such as characteristics of the model, which determine the current output of the model. In a comparison of this output with real data, we feel that it is reasonable that the model predicts a higher prevalence than currently is recognized in the field.

3.3 Limitations of modelling

Because the results of this study are based on a simulation model, one should remember the fact that models are always a simplification of reality. The main focus of our model was on simulating the prevalence of contaminated beef-carcass quarters; the actual number of VTEC O157 CFU on the surface of the contaminated beef quarters was calculated based on a relatively simple approach. We chose not to model the exact number of bacteria transferred from sources to the beef surfaces along the slaughter line because this requires a lot more assumptions and data. Decision makers currently seem to focus on the prevalence of contaminated carcasses, and this focus was used in other research (Van der Gaag et al., 2004; Alban and Stark, 2005). However, we acknowledge that the ignorance of the number of bacteria transmitted to the end product could be undesirable from the public-health point of view. In the model we assumed that each quarter receives a fourth of faecal contamination. This might have an impact on the output, but to avoid adding more assumptions, the process of the distribution of manure between the quarters was not modelled. Furthermore assumptions had to be made to calculate the reduction of the probability that the bacteria were eliminated from the carcasses through different decontamination measures. This depends highly on the initial number of bacteria. The initial number of CFU was determined on the basis of distributions of the amount of manure and the concentration of CFU in the manure. These distributions were based on a Dutch expert's opinion and literature (Zhao et al., 1995; Nauta, 2001). The distribution of the bacterial concentration might vary for the Netherlands and the distribution of the transferred manure might be different than in the conditions considered in the reference study. Therefore, the elimination probability used in our model could under or overestimate the effectiveness of interventions.

Culled dairy cattle are the main source of beef in the Netherlands and consequently the population of beef cattle is rather low (119,000 beef cows vs. 1,500,000 dairy cows). Therefore, the model focuses only on dairy cattle. However there is a relatively large veal-production sector in the Netherlands. The prevalence of VTEC O157 is different in the dairy sectors and the veal. Also, the veal sector has separate slaughterhouses. Thus, the model needs some adjustment to be used for veal slaughterhouses.

A last point to be noted is that, under the current EU policy and regulation (February 2006), washing carcasses with organic acids (e.g., lactic-acid rinse) and irradiating red meat is prohibited (Heuvelink, 2000; Duffy, 2002; EU, 2003). On the other hand, steam-pasteurization and steam-vacuuming of cattle carcasses are not methods commonly being used in European countries. In case of possible changes in EU policies and more demand for implementing extra decontamination measures in the current slaughter process, the results of this study could be useful in a future discussion of which interventions should be allowed and applied.

4. CONCLUSIONS

We predict that the prevalence of VTEC O157-contaminated quarters of dairy beef can be decreased by roughly one-third to one-sixth by implementing any one of six decontamination methods. However, we predict that using multiple methods generally would decrease quarter-level prevalence by substantially more than most single-method strategies. Under our assumptions, irradiation at the end of the process would decrease prevalence by >99%, only reachable otherwise by combing five of the six other methods.

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Appendix to chapter 2

Colony forming unit (CFU) or prevalence: How to use experimental data in prevalence simulation modelling

Paper by Vosough Ahmadi B., Velthuis A.G.J., Hogeveen H., Huirne R.B.M. Published in the proceedings of the annual conference of the Society for Veterinary Epidemiology and Preventive Medicine (SVEPM), Exeter, United Kingdom (2006).

SUMMARY

The effectiveness of antimicrobial decontamination methods in slaughterhouses can be expressed as reduction in number of colony forming units (CFU) counts and as a reduction in prevalence of contaminated end products. In many risk assessments the contamination status of the food products are modelled, with prevalence as output parameter. To use experimental microbiological data in these models, indicating the CFU reduction after an applied intervention, these data should be translated into a probabilistic input parameter. We present a methodology to calculate such a probability from experimental data. Using this methodology it is demonstrated that the effectiveness of decontamination methods varies with the initial number of bacteria present on the carcass. And in case of a high initial concentration of bacteria (>log 5), the elimination probability will be zero even if a very powerful decontamination method is applied.

1. INTRODUCTION

Carcass antimicrobial-decontamination methods are considered as slaughterhouse interventions against enteric pathogens such as *E. coli* O157:H7 (VTEC O157) (Koohmaraie et al., 2005). The effectiveness of decontamination methods is an element that should be considered in a cost-effectiveness analysis. Two measures of effectiveness of decontamination methods at the slaughterhouse can be distinguished: (i) reducing the fraction (i.e., prevalence) of contaminated carcasses and (ii) reducing the number of bacterial colony forming units (CFU) on a carcass. When focusing on food-safety problems related to the enteric pathogens that may contaminate meat, models that predict the number of CFU counts (see for example Ebel et al., 2004; Nauta, 2001) are suggested. However, such models require a large number of input variables and thus many assumptions. Prevalence simulation models are often used to estimate the effectiveness of intervention strategies to reduce the fraction of carcasses contaminated by enteric pathogens (see for example Alban and Stark, 2005; van der Gaag et al., 2004b). The advantage of prevalence simulation models is that less input variables and thus fewer assumptions are needed.

Results of experimental studies are often expressed in terms of log reduction of CFU counts on the surface of the meat (Juneja and Sofos, 2002; Phebus et al., 1997; Retzlaff et al., 2004). If we want to use these data in a prevalence simulation model, an approach needs to be developed to convert the reported log reduction to an elimination probability, which is the probability of eliminating all the bacteria from surface of the meat using decontamination methods. Although, there have been some efforts to translate a pathogen reduction into an elimination probability (SCVPH, 1998, 2003) they were not satisfying. Their focus was mainly on converting percentage reduction of CFU counts by decontamination methods into the proportion of positive carcasses and not on translating the experimental data to an elimination probability. More studies are therefore needed to introduce and examine other approaches. In this paper, we demonstrate a modelling approach that can be used to translate an experimentally measured log reduction (of decontamination methods) to an elimination probability. Such elimination probability can be used in a prevalence simulation model to evaluate the effectiveness of decontamination methods. In the following sections first the modelling approach is presented and then, using some published data for the initial number of bacteria and the antimicrobial effects of the decontamination methods, this modelling approach is illustrated in a prevalence model.

2. MATERIALS AND METHODS

2.1 Modelling approach

The aim of this modelling approach is to estimate the elimination probability for antimicrobial decontamination methods, given different values of the initial number of pathogens on the surface of the carcasses. The reduced number of CFU resulting from implementing a decontamination method is translated into the probability of having zero bacteria (i.e. the elimination probability) using the first element of a poisson distribution. The expected number of CFU per carcass after intervention equals the initial number of CFU on each carcass minus the reported CFU reduction due to that intervention. Let *EP* denotes the estimated elimination probability, μ the initial number of CFU on the whole carcass and λ the reduction in number of CFU on the whole carcass. The elimination probability can be calculated using following equation:

$$EP = e^{-(\mu - \lambda)} \qquad (1)$$

Using equation (1) the relation between *EP*, μ and λ has been illustrated (Figure A2.2). For this illustration, seven different decontamination methods with antimicrobial effectiveness varying from one to seven log reduction of CFU (log 1 to log 7) were assumed. The results of this methodology are given in the result and discussion section.

2.1.1 Application

The modelling approach described above, was developed to investigate the effectiveness of interventions (in terms of reduction in prevalence) against VTEC O157 in Dutch beef industrial slaughterhouses (Vosough Ahmadi et al.). Five carcass-decontamination methods, hot-water wash, lactic-acid rinse, steam vacuum, steam pasteurization and gamma irradiation including their combinations were examined. With a Monte Carlo simulation the elimination probabilities for the decontamination methods were calculated using published data for antimicrobial effectiveness of the decontamination methods and the initial number of bacteria on the surface of the beef carcass (Figure A2.1). The area separated by the dashed line in Figure A2.1 is the model to estimate the elimination probability presented in this paper. The output of this model serves as input in the prevalence simulation model, which uses binomial processes (Vosough Ahmadi et al.). The initial number of bacteria (CFU) on each carcass was simulated by multiplying two distributions: the amount of transferred manure in grams to the carcass (beta distribution) and the concentration of VTEC O157 in one gram of manure (cumulative distribution). The used data and distributions were based on a VTEC O157 risk assessment (Table A2.1, Nauta, 2001). A beta distribution to describe the carcass contamination with manure was chosen after fitting the results of expert estimates to a series of probability distributions (Nauta, 2001). The parameters α and β are used to express the level of carcass contamination with manure and its variability per carcass. A cumulative distribution was used to include the uncertainty related to the concentration of VTEC O157 in a gram of manure, based on data reported by Zhao (Zhao et al., 1995). In the mentioned study, VTEC O157 concentrations in the faeces of 31 positive calves were measured from a survey of dairy herds in the U.S.

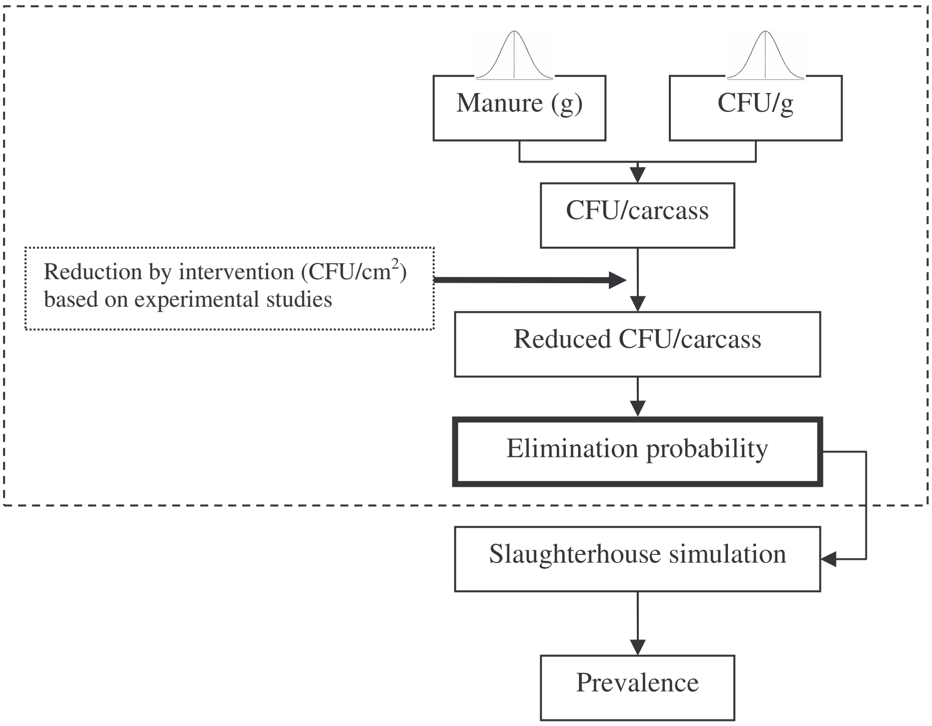

Figure. A2.1 Schematic view of VTEC O157 simulation model

For the simulations we assumed that each carcass has a total surface of 32,000 cm^2 and that each quarter receives equally one fourth of the total faeces. The expected number of CFU per quarter when interventions are applied equals the initial number of CFU (μ) on each quarter minus the reported reduction (λ) due to a specific intervention (Phebus et al., 1997). The reduced number of bacterial counts resulting from a reduction due to intervention is calculated by equation (1). The mean elimination probabilities were determined using 10,000 iterations and were used as inputs in the VTEC O157 prevalence simulation. The model was built in Microsoft Excel spreadsheet using @Risk add-in software.

Table A2.1. Description of variables and distributions used in the VTEC O157 simulation model

variable	Distribution	Values
Concentration of bacteria (log CFU) in gram of manure	Cumulative [a]	{X_i: 0, 2, 3, 4, 5, 6} {P_i: 0.00, 0.46, 0.53, 0.87, 0.96, 1.00}
Gram of manure on each Carcass	Beta [b]	Max: 10.1 α: 0.395, β: 2.47

[a] @Risk function: RiskCumul(0,6, {2,3,4,5},{0.469, 0.531, 0.875, 0.969})
[b] @Risk function: Max * RiskBeta(α, β)

3. RESULTS AND DISCUSSIONS

Figure A2.2 shows the elimination probabilities for the seven assumed categories of decontamination methods (log 1 to log 7) with different values for the initial number of bacteria present on the carcass. The elimination probability will be zero when applying a weak decontamination method (log 1 reduction in CFU) on a carcass that is initially contaminated with more that 68 CFU (log 1.8). At that level of initial contamination, more powerful decontamination methods give a high elimination probability of infection. However, with a higher level of initial contamination, also more powerful decontamination methods may give zero elimination probability. The elimination probability for decontamination methods with antimicrobial effects of log 6 and log 7 will be zero only if the initial CFU count is higher than one million. These results imply that in the case of having very high initial concentration of bacteria on the carcasses (>log 5), the elimination probability can be zero even if a powerful decontamination method is applied. This means that interventions will have no effect on the reduction of the prevalence of contaminated carcasses. However, these decontamination methods still give an important improvement of the beef safety by reducing the CFU counts.

Figure A2.2 also shows that the elimination probability will be higher than zero when the initial number of bacteria is low (<log 1.8), and therefore a prevalence reduction can be expected using these methods. The majority of the decontamination methods have an elimination probability greater than 90% in the case of having up to 10 CFU (log 1) as initial number of bacteria. These values decline by increasing the initial bacterial load. This result implies that control of the initial contamination of the carcass is effective in two ways. It lowers the prevalence of contaminated carcasses directly and it increases the elimination probability of existing infections.

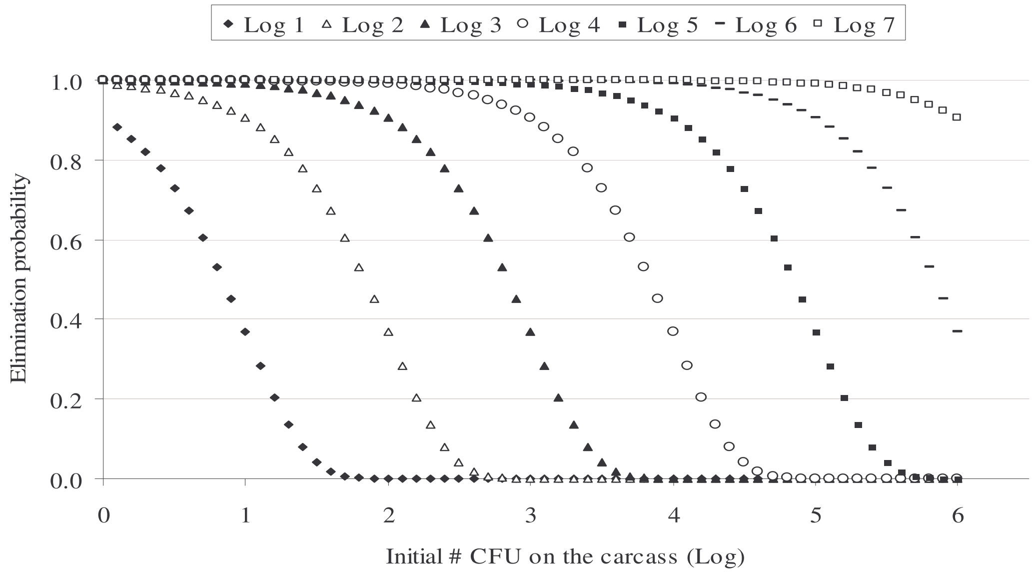

Figure A2.2. Elimination probabilities for seven decontamination categories graphed against different levels of initial number of CFU on the carcass in log scale

In the application part of the modelling approach explained in this paper, the data on initial number of bacteria on the carcass and experimental data on antimicrobial effects of decontamination methods were used to estimate the mean elimination probability for each decontamination method. The eventual goal was to use the estimated elimination probabilities in a prevalence simulation model to estimate the effectiveness of decontamination methods in reducing the prevalence of contaminated beef-carcass quarters. To get stable output, the elimination probabilities for the five decontamination methods were calculated with 10,000 iterations. The antimicrobial effects (input) and mean values of elimination probabilities (output) of the five decontamination methods are presented in Table A2.2. The practical meaning of these values is that, for example, when hot-water wash is used as intervention, a contaminated beef-carcass quarter will have a 34% probability of changing from positive to negative. In this way, these values can be used in prevalence simulation models that are developed based on binomial processes. Because of the low initial number of bacteria coming from the two mentioned distributions, in most cases the most-likely values for the elimination probabilities were close to one. Thus, choosing the mean of the distribution assures us to consider the tail of the distribution.

In general, the reduction in prevalence depends highly on the initial number of bacteria on the surface as well as the antimicrobial power of decontamination method used. The antimicrobial power of decontamination methods depends on different factors such as the technical strength of decontamination methods to destroy the bacterial germ, time and place of intervention (in the slaughter line) as well the type of the bacteria and its adherence characteristics to the meat surface. Therefore, both prevalence reduction and CFU reduction effects should be considered when the "effectiveness" of decontamination methods is concerned. In the majority of the cost-effectiveness analyses on the interventions against enteric bacteria, the main focus is only on one of the mentioned effects. For example Jensen et al., (1998) consider only CFU reduction and van der Gaag et al., (2004a) consider only prevalence reduction as the basis of their economic analysis. This may lead to an underestimation of effectiveness (in case of focusing only on experimentally measured CFU reduction) or overestimation (in case of focusing only on prevalence reduction). Thus efforts should be done to consider these factors together in such studies.

Table A2.2. Mean elimination probability for five decontamination methods

Decontamination	Mean reduction [a] (log CFU/cm^2)	Mean Elimination Probability (%)
Hot-water wash (W)	0.75 ± 0.49	34.69
Lactic-acid rinse (L)	2.70 ± 0.49	68.75
Steam vacuum (V)	3.11 ± 0.49	77.00
Steam pasteurization (S)	3.53 ± 0.49	83.17
Irradiation (Ir)	6.00 ± 0.49 [b]	99.48

[a] Mean reduction in VTEC O157 population (log CFU/cm2) ± standard error of mean (Phebus et al., 1997).

[b] Molins et. al.(Molins et al., 2001), the same standard error as the other methods is assumed.

In the relatively simple simulation model described in this paper, the initial number of CFU was determined based on distributions for the amount of manure and the concentration of CFU in the manure. These distributions were based on the Dutch expert's opinion and literature (Nauta, 2001; Zhao et al., 1995). Because the type of the distributions was based data fitting, as explained by Nauta (2001), these distributions may vary in other countries and conditions. Therefore the elimination probability calculated for each decontamination method might be different for different countries and conditions. This is mainly due to the hygienic measures in the slaughterhouses that allows or prevents the transmission of manure to the carcasses. Also this depends on the concentration of CFU bacteria shed into the manure. Farming practice and the situation of different countries are important factors for concentration of bacteria shed in the manure.

4. CONCLUSIONS: PREVALENCE VERSUS CFU MODELLING

Looking at the prevalence versus CFU modelling issue, on one hand we observe that industry, regulatory agencies and consumers focus on the fraction (prevalence) of contaminated end products. Also many scientific studies focus only on prevalence. As it was mentioned before, in the case of a low initial contamination (i.e. lower than 1.8 log CFU count), focusing on prevalence can be a good approach without modelling or considering the CFU counts. This seems a valid assumption for the common slaughter practice in most of the developed countries. However risky events such as gut rupture during the evisceration, which can lead to the release of a large number of bacteria on the carcass, can make this assumption not valid even in the best manufacturing practices at slaughterhouses.

On the other hand public health authorities and farm-to-fork risk assessors are very much concerned about the exact number of CFU present on the surface of the meat. As the infectious dose for some of the enteric pathogens such as VTEC O157 is very low, even one bacterium has a great importance. Therefore, from this point of view studies that consider prevalence as their main criterion do not sufficiently address the problem. In this case the result of the effectiveness analysis may become biased because of the overestimation of the effectiveness.

Thus, it can be concluded that in the effectiveness analysis of decontamination methods the expected number of CFU on the carcasses along with the consideration of the expected prevalence of contaminated carcasses should come together. The best way to this is to develop a CFU model that estimates the number of transmitted bacteria to the end product and thus implicitly estimates the prevalence of contaminated product as well. An alternative way that presented in this paper is modelling the elimination probabilities based on initial CFU contamination and feed them as input to a prevalence simulation model to calculate the prevalence reductions due to specific decontamination methods.

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Chapter 3

Cost-efectiveness of beef slaughterhouse decontamination measures in The Netherlands

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SUMMARY

The cost-effectiveness of seven decontamination measures to reduce *E. coli* O157:H7 (VTEC O157)-contaminated carcass quarters in a typical Dutch beef industrial slaughterhouse were explored. To estimate the effectiveness a stochastic epidemiological-simulation model was used and to estimate the net cost a deterministic-economic model. The estimated baseline prevalence of daily contaminated quarters was 9.16% (with a 90% confidence interval 4.40%-13.10%). A reduction in the prevalence of VTEC O157-contaminated quarters to 2% using decontamination measures is achieved at costs of €0.20 to €0.50 per quarter which is 16% to 40% of the net profit per carcass. A reduction to a prevalence of 1% will cost €0.50 to €1.00 per quarter. Additional carcass trim and carcass steam-pasteurization are considered as the most cost-effective decontamination measures with costs of €16,340 and €20,243 per year to achieve a 1% prevalence reduction. Nevertheless, the lowest level of VTEC O157 prevalence, less than 1%, is achieved using a set of measures which costs between €1.00 to €2.00 per quarter or, by implementing irradiation which costs €4.65 per quarter.

1. INTRODUCTION

E. coli O157:H7 (VTEC O157 in this paper) is a food-borne pathogen, that can be ingested with contaminated beef. The number of human cases in the Netherlands is estimated to be 1,250 cases per year (Havelaar et al., 2004). Despite of the relatively low number of cases, the symptoms and health consequences are severe. It has been shown that the VTEC O157 is present in the Dutch food chain (Heuvelink et al., 2001; Heuvelink et al., 1999; Heuvelink et al., 1998; Heuvelink et al., 1996) and the possibility of outbreaks due to consumption of contaminated food cannot be excluded. Therefore, to protect public health, measures to prevent the spread of VTEC O157 in the food chain are important to consider.

VTEC O157 can be present in the gastrointestinal (GI) tract and on the hide of cattle and consequently in the environment of the slaughterhouse. It can be transmitted to the surface of the carcasses during the slaughter process. The control of VTEC O157 in the slaughterhouse focuses on the reduction of existing contaminations as well as the prevention of new contaminations. Along the cattle-slaughter line some measures are already in place to prevent contamination of carcasses with bacteria, e.g. trimming and extra hygiene. However, even under the best hygienic management, transfer of the enteric bacteria such as VTEC O157 to the surface of the carcasses seems inevitable in the current slaughterhouses (Koohmaraie et al., 2005). In a recent study VTEC O157 has been recovered from 3% (4 out of 132) of the carcass samples in a beef slaughterhouse in Ireland (O'Brien et al., 2005). In a study in the Netherlands, no VTEC O157 was isolated from the carcass samples, while more than 10% of carcasses were visibly contaminated with faeces in 11 of the 27 slaughterhouses and more than 50% of the inspected carcasses were visibly contaminated with faeces in 6 slaughterhouses (Heuvelink et al., 2001). Although VTEC O157 was not recovered from the carcass samples, the presence of bacteria on cattle farms and the fact that carcasses are sometimes contaminated with faeces imply that preventive measures at Dutch cattle slaughter plants should receive attention.

In this study we considered a typical Dutch dairy-industrial slaughterhouse, with a capacity of 500 dairy cattle per day (125,000 cattle/year). Seven industrial dairy-beef slaughterhouses are currently active in the Netherlands and their slaughter capacity varies between 25,000 to 360,000 cattle per year (PVE, 2005). The annual number of cattle slaughtered in the nation is 615,000 cattle. Production of dairy-beef is 188,000 tonnes per year. In 2004, a total of 672,500 live cows of which most are intended for slaughter are imported every year. The total yearly dairy-beef and beef products (slaughtered in the Netherlands) are estimated as 184,000 tons. Around 308,000 of beef and beef products are imported and 200,000 tons exported. The domestic beef consumption is estimated as 293,000 tones per year. Beef represents almost 21% of the overall meat consumption of the Dutch consumers. Dairy-beef production price is estimated as 1.90 €/kg, while the prices at retailer are 8.27 €/kg (PVE, 2005). The slaughtering of animals is increasingly bound to rules and regulations. Most of these regulations are focusing on quality and food-safety. Next to IKB-principles, since 2002 HACCP principles have been introduced to this sector. Adding one or more measures such as decontamination measures studied in this paper, increases the production costs and enhances the beef-safety. This paper tries to build an epidemiological-economic framework to study the mentioned consequences of implementing decontamination measures.

A stochastic-epidemiological model to evaluate the effectiveness of decontamination measures to control VTEC O157 in a typical Dutch industrial cattle slaughterhouse was developed (Vosough Ahmadi et al., 2006b). The effectiveness of seven decontamination measures and their combined sets have been reported in terms of the ability to reduce the proportion of contaminated beef-carcass quarters at the end of the quartering stage and the ability to reduce the number of colony forming units (CFU) of bacteria present on the surface of the quarters. The reduction of CFU measured in experimental studies was translated to the probability to eliminate the bacteria from the surface of the meat (Vosough Ahmadi et al., 2006a; Vosough Ahmadi et al., 2006b). However, because slaughterhouses are business firms and run under economic constraints, effectiveness alone cannot be the only criterion used by decision makers to decide to invest in these decontamination measures. Therefore, the economic effectiveness of these measures should also be determined. Jensen et. al., (1998) evaluated the costs of implementing carcass decontamination measures to improve food safety in the meat sector in US. In that study, the effectiveness were used based on the reducing the number of bacterial colony forming units (CFU) from the surface of the meat in US industrial slaughterhouses that have much larger capacity than in the Netherlands. However, there has been no study on the cost-effectiveness of the decontamination measures against VTEC O157 where the effectiveness being considered as both reducing the prevalence of contaminated carcasses and reducing the number of CFU. To fill this gap the study presented in this paper was performed.

The objectives of this paper are: (i) to determine the costs of applying different decontamination measures in industrial beef slaughterhouses and (ii) to rank the measures and combined sets based on their cost-effectiveness. The cost-calculations are based upon Dutch circumstances.

2. MATERIALS AND METHODS

To determine the cost-effectiveness of decontamination measures in an industrial slaughterhouse, two models were used: an epidemiological and an economic model. The epidemiological model was used to estimate the level of expected effectiveness by each decontamination measure. The economic model was developed additional to the epidemiological model to calculate the costs of each measure per carcass quarter.

2.1 The epidemiological model

The epidemiological model has been described in detail earlier (Vosough Ahmadi et al., 2006b). A Dutch industrial beef slaughterhouse with a slaughter capacity of 500 cattle per day was modeled. Carcass fore- and hind-quarters were considered as the end product of the model and Monte Carlo simulation was used to simulate the number of contaminated beef-carcass quarters per day at the end of the quartering stage. One iteration of the model (out of 10,000 iterations) represents one slaughter day in which 2,000 quarters are produced. Nine stages of the slaughter process were included: (1) lairage; (2) de-hiding; (3) evisceration; (4) splitting; (5) fat and tail removal; (6) trim; (7) washing (to lower the carcass temperature); (8) chilling; and (9) quartering. The VTEC O157-contamination status of each individual carcass, half carcass and quarter at every stage of the slaughter process was modeled. The model was built in Microsoft Excel spreadsheet using @Risk add-in software (Palisade, 2002).

Within each modeled stage of the slaughter process the status of a carcass can change form negative (not-contaminated) to positive (contaminated) by two contamination routes. The status of a carcass can change from positive to negative by a decontamination route. Corresponding to these routes three probabilities can be recognized: (i) the probability of transferring VTEC O157 onto the carcass by means of the main risk factor of that specific stage (e.g. probability of GI rupture during the eviscerating operation), (ii) the probability of transferring the bacteria from the environment onto the carcass and (iii) the probability of eliminating the bacteria from the carcass by means of an antimicrobial decontamination measure (Phebus et al., 1997). In this model, quarters contaminated with no bacteria (zero CFU) are defined as negative or not contaminated. On the other hand, quarters with at least one CFU on their surface are defined as positive or contaminated. In other words the model estimates the true prevalence, while in epidemiological studies the apparent prevalence is estimated.

The elimination probability for each intervention was calculated based on results of experimental studies that are expressed as reduction in logCFU/cm^2 of the initial bacterial population. Because the number of CFU on each quarter follows a poisson distribution, the probability of having zero CFU was calculated from the expected number of CFU on a quarter after applying the intervention (λ). λ equals the initial number of CFU on each quarter minus the reported reduction due to a specific intervention (Phebus et al., 1997). The initial number of bacteria (CFU) on each quarter was simulated by multiplying two distributions: the amount of manure (in grams) transferred to the carcass and the concentration of VTEC O157 in one gram of manure. To give an example, steam-pasteurization can reduce the initial number of bacteria by 3.53 logCFU/cm^2. Given our assumptions, this corresponds to an 83% probability of eliminating all the bacteria from a quarter.

Various decontamination methods can be applied along the whole slaughter process. Antimicrobial interventions can reduce the number of bacteria on the carcass surface, and in the case of elimination of all bacteria they can change the contamination status of the quarter (Smulders and Greer, 1998). In this study we considered the seven decontamination methods in the beef industry: hot-water wash (W); trim (T); steam-vacuum (V); steam-pasteurization (S); lactic-acid rinse (L); irradiation (Ir) and hide-wash with ethanol (H). We compared their effectiveness used individually or in combination. The combinations of interventions were chosen in such a way as to be consistent with the combinations that were mentioned in the reference study (Phebus et al., 1997), and those are combinations that are technically more justifiable. The model was run with two or more interventions implemented in different places along the slaughter line to estimate the effectiveness of combinations.

The number of infected cattle (in the GI tract or on the hide) entering the slaughter line was simulated based on a herd-level prevalence of 7.2%, an animal-level prevalence of between 0.8% and 22% and a hide-level prevalence with a minimum of 6.7%, mode of 32.9% and maximum of 42.3%.

2.2 Cost-calculation method

Every decontamination measure has one or more elements that have costs associated with them. These elements can be divided into five main categories: (1) personnel; (2) facilities (e.g., land and building); (3) equipment (e.g., machinery); (4) volume of materials used (e.g., disinfection fluids) and (5) miscellaneous (e.g., energy and transport) (Levin, 1983). By identifying the elements and their costs, the total costs of the measures can be estimated. These costs are determined per year and per carcass quarter.

Table 3.1. Definition and classification of the costs for elements in decontamination measures

Recurrent costs (€/year)	RC_j	Non-recurrent costs (€)	NRC_j
Additional labour	*l*	Facilities (land, building)	*f*
Volume of additional materials	*v*	Purchase (machinery, installation etc.)	*p*
Miscellaneous (energy, etc.)	*s*	Life time in years (for depreciation)	*n*
Maintenance	*m*		

Within each element, non-recurrent costs and recurrent costs can be distinguished (Mangen et al., 2005; Hongren et al., 2000). Non-recurrent costs take place only once in the beginning of the item's life time and should be considered along the life time of that element. New buildings that are needed for implementing one of the decontamination measures as well as investments in equipment are considered as non-recurrent costs (Table 3.1).

Let *f* and *p* denote the cost elements corresponding with non-recurrent items facilities and purchase costs for equipment respectively, then the non-recurrent costs (NRC) for decontamination measure *j* per quarter for building and machinery are calculated as follows:

$$NRC_j = f_j + P_j \tag{1}$$

Non-recurrent costs were depreciated based on an efficient life-time of 15 and 7 to 8 years for buildings and equipment respectively, assuming no salvage value of the items at the end of the life time. Interest was calculated on the average value of the investment with a yearly interest rate of 4%. If *n* denotes the total years corresponding with actual life-time of the building and machinery to depreciate non-recurrent costs and *i* as interest rate, the formula used for the annuity (*A*) of interventions *j* is:

$$A_j = NRC_j \times \left(\frac{i \times (1+i)^n}{(1+i)^n - 1} \right) \tag{2}$$

In contrast to non-recurrent costs, recurrent costs (RC) of measure *j* are costs due to a cost element that occur every day, week or year. The recurrent costs for each measure were calculated by summing up the annual maintenance expenses *m* (one percent of their investment costs) for *N* number of annually produced beef-carcass quarters, the yearly costs of additional labour *l*, the yearly costs of additional material used *v* (e.g., ethanol) and miscellaneous items that are consumed in addition to the normal production process *s* (e.g. energy and water):

$$RC_j = m_j + \left(\frac{(l_j + v_j + s_j)}{N} \right) \tag{3}$$

The total cost (TC) of measure *j* (€/quarter) is calculated by summing up the recurrent and the estimated annuity (*A*) of the non-recurrent costs:

$$TC_j = RC_j + A_j \tag{4}$$

2.3 Cost items of selected decontamination measures

Seven well-described decontamination measures that can be applied in beef slaughterhouses were included in this study. Some technical peculiarities of these measures that affect the implementation costs are explained next.

1- Hot-water wash (W). With this method carcasses are washed with water of >74ºC while passing a washing cabinet. This method requires purchasing equipment (water heating facilities and a washing cabinet). No additional labour is needed because it is fully automatic. The non-recurrent costs include the heating of water where following cost elements are considered: additional water, additional natural gas, additional electricity, water refining or effluent costs and maintenance. Note that in the current Dutch slaughterhouses the carcasses are washed with cold water to reduce the carcass temperature just before entering the chilling room.

2- Additional trim (T). Trimming is the removal of visually detectable contamination spots from the surface of the carcass with a round knife. This activity is already part of the slaughter process in the Netherlands and is applied after the splitting stage. In this study we quantified the costs of additional trimming which is labour consuming. Special round knives are used, which needs an additional investment.

3- Steam-vacuum (V). With this method, steam is sprayed on visually detectable contaminated spots on the surface of the carcasses, followed by vacuuming which has the combined effect of removing and inactivating surface contamination. Like trim, additional labour is needed for this method. This method can be applied post evisceration or post splitting. The main part of the non-recurrent costs and recurrent costs for this decontamination measure is due to the steam production where additional natural gas, water and electricity are needed.

4- Steam-pasteurization (S). With this method, condensed steam is being used for the destruction of bacteria on the surface of the carcass. The commercialized system of steam pasteurization consists of a cabinet in which carcasses are treated by steam and thereafter, they are immediately chilled by spraying cold water. This operation can take place before the half-carcasses enter the chilling room. This system is widely in use at large cattle slaughter plants in US (Edwards, 2006; Phebus et al., 1997). Non-recurrent costs are the investment and installation. It was assumed that there is enough space to install this equipment in the plant, so that no additional land and building are needed. Recurrent costs are water, electricity and natural gas.

5- Lactic-acid rinse (L). With this method, lactic acid (2% solution) is rinsed on the surface of the carcasses during their passage through a washing cabinet before the chilling stage. Similar to the hot-water wash, this is an automated procedure, however one additional worker is needed to prepare the acid solution and supervise the system. Besides lactic acid and additional water used, natural gas and electricity are necessary to warm up the lactic-acid-water solution.

6- Irradiation (Ir). With this method, gamma irradiation is used to kill the pathogens present on the outer surface and in some extent in the inner layers of the meat. This method is mostly being used after the meat-packaging stage. However, to make a comparison between the available methods, it is assumed that carcass quarters are irradiated at the end of the quartering stage. Furthermore, it is assumed that an irradiation facility is not on-site but at a specialized plant to which the quarters are transported. No non-recurrent or investment costs for the beef slaughter plant are involved. The recurrent costs include transportation and a fee for irradiation. The fee is based upon the mean weight of a carcass, which is considered to be 320 kg (Nauta, 2001). Four additional workers are needed for loading, unloading and administrational jobs at the slaughter plant. Each transportation truck carries 250 quarters and therefore around 2,000 trucks are needed per year.

7- Hide-wash with ethanol (H). With this method the hide of animals is being washed by a high concentration of ethanol (90% solution) before they enter the slaughter line. It was assumed that an additional lairage is needed (210m^2 for 120 animals) to keep the washed animals separated from the unwashed animals. For this an additional building and land are needed. The new lairage construction is built with a cost of €546/m^2. Three additional workers are needed to wash the cattle. Next to the building, the land and additional equipment (pumps and attachments), recurrent costs consist of ethanol consumption and the electricity. The amount of ethanol needed is estimated at 4.8 litre per cattle (Mies et al., 2004). It is assumed that the system is not a closed circle and that used ethanol is not being reused. Almost no additional water is needed since the ethanol is purchased in the proper dilution. The recurrent costs were due to consumed electricity for running the pumps.

2.4 Quantification of cost items

Appendices 3.1 and 3.2 summarize the quantified economic inputs used for the cost calculations. This quantification has been based on interviews with the Dutch industrial slaughterhouse experts and by using scientific literature and internet. Seven existed industrial Dutch beef slaughterhouses were contacted to participate in this study and three were willing to participate. We interviewed two quality control managers and one general manager. Information on investment costs for required machineries for various decontamination measures were provided by slaughterhouse equipment producing companies and searching the internet and literature. Prices for the consumed materials are assumed to be fixed however, for some inputs such as the number of additional workers needed, the purchase costs of equipment and the labour costs, minimum, most-likely and maximum values were determined. Most-likely values were used as default and the minimum and maximum values were used in the sensitivity analysis. To estimate the costs of combinations of interventions, the cost items which can be shared to run more than one interventions were identified to prevent double counting. As an example, it was assumed that the steam-producing equipment can be used both for steam-vacuum and steam-pasteurization. For the other items total costs of a combination set was estimated by summing up the costs of individual interventions.

2.5 Calculation of cost-effectiveness

The costs of the decontamination measures (ΔC) were calculated with the economic model and the effectiveness, in terms of the reduction of prevalence (ΔP) and the reduction of CFU/cm^2 (ΔCFU) were estimated with the epidemiological model. Intervention strategies consisted of single or combined decontamination measures. To rank the measures cost-effectiveness (or effectiveness-cost) (CE) ratios were calculated (Belli, 2001):

$$EC_{Pj} = \Delta P / \Delta C_{quarter} \quad (4)$$

$$EC_{CFUj} = \Delta CFU / \Delta C_{quarter} \quad (5)$$

$$CE_{Pj} = \Delta C_{year} / \Delta P \quad (6)$$

To get a more comprehensive insight on the cost-effectiveness ratios, the least-cost frontier for prevalence reduction and CFU reduction were determined. This is done by graphing the costs per quarter against the effectiveness (ΔP, ΔCFU) and connecting the points with the least cost and highest effectiveness.

2.6 Sensitivity analysis

In the baseline scenario, the most-likely values of the parameters were used. With help of a univeriate sensitivity analysis the impacts of the uncertain parameters on the output was investigated. The results of the cost-effectiveness ratios were compared with the ratios calculated based on the minimum and maximum values for the parameters and the 5th and 95th percentiles values for reduction in prevalence. In other words, cost-effectiveness ratios (CE_{Pj}) were calculated using the 5th and 95th percentile values for the effectiveness and the default values for the costs and cost-effectiveness ratios were calculated using the default values for effectiveness and minimum and maximum values for the costs:

$$CE_{Pj} = \Delta P_{5th;95th} / \Delta C \quad (7)$$

$$CE_{Pj} = \Delta P / \Delta C_{\min;\max} \quad (8)$$

3. RESULTS

Various elements for recurrent and non-recurrent costs of the seven decontamination measures were identified and the total additional costs per carcass quarter and on a yearly basis were calculated (Table 3.2). The total costs of decontamination measures ranges from €0.22 (hot-water wash or trim) per quarter to €4.65 (irradiation) per quarter. Steam pasteurization, lactic-acid rinse and steam vacuum are in the same range of the total costs per quarter, around €0.35. Ethanol-hide wash has total costs of €0.65 per quarter, which makes it the second most expensive decontamination measure. In all the cases, recurrent costs are higher than the non-recurrent costs. Steam pasteurization had the highest non-recurrent costs at €0.07 per quarter where additional trim showed the lowest €0.02. Irradiation and ethanol-hide wash had the highest recurrent costs, i.e. €4.56 and €0.61 per quarter, respectively, where hot-water wash had the lowest, i.e. €0.18 per quarter.

Table 3.2. Non-recurrent costs (NRC), recurrent costs (RC) and total costs (€/quarter carcass) of decontamination measures

Costs	Hot Water Wash (W)	Lactic Acid Rinse (L)	Additional Trim (T)	Steam Vacuum (V)	Steam Pasteurization (S)	Ethanol Hide Wash (H)	Irradiation (Ir)
Non-recurrent (€/quarter)							
Equipment	0.0295	0.0560	0.0200	0.0325	0.0698	0.0042	-
Installation	0.0065	0.0006	-	-	0.0005	-	-
Shipping	0.0006	0.0004	-	0.0004	0.0003	-	-
Spare parts	0.0004	0.0006	0.0006	-	0.0001	-	-
Building	-	-	-	-	-	0.0268	-
Total NRC (€/quarter)	0.0370	0.0576	0.0206	0.0329	0.0707	0.0310	-
Recurrent (€/quarter)							
Land lease	-	-	-	-	-	0.0002	-
Labour	-	0.1000	0.2000	0.2000	0.1000	0.3000	0.4500
Electricity	0.0055	0.0055	-	0.0007	0.0052	0.0033	-
Water	0.0174	0.0180	-	0.0080	0.0106	-	-
Natural gas	0.1575	0.1575	-	0.1144	0.1144	-	-
Solutions	-	0.0143	-	-	-	0.3120	-
Effluent	0.0043	0.0067	-	0.0011	0.0026	-	-
Transport	-	-	-	-	-	-	1.0000
Process fee	-	-	-	-	-	-	3.2000
Total RC (€/quarter)	0.1847	0.3020	0.2000	0.3242	0.2328	0.6155	4.6500
Total Costs (€/quarter)	0.2217	0.3596	0.2206	0.3571	0.3035	0.6465	4.6500
Costs for slaughterhouse/year	110,850	179,800	110,300	178,550	151,750	323,250	2,325,000

Table 3.3 shows the results of the epidemiological and economic models as well as the cost-effectiveness ratios. The estimated prevalence of daily contaminated beef-carcass quarters by the epidemiological model for the baseline scenario was 9.16% (where 4.40% and 13.10% were the 5th and 95th percentiles). Details of the model and the results can be found in Vosough Ahmadi et al.(2006b).

Additional trim and steam pasteurization were in the first and second rank in both CE_P and CE_{CFU} ratios. For a 1% reduction of the prevalence, additional trim and steam pasteurization generate annual costs of €16,340 and €20,233 respectively. Some differences in the ranking occur when using CE_P and $CE_{CFU.}$ The rank of hot-water wash varied most (i.e. rank 7 based on CEp and rank 13 based on CE_{CFU}). Increasing the number of decontamination measures in a combined set resulted in a lower CE ratio and thus a lower ranking for both CE types. The combined set of hot-water wash, lactic-acid rinse, steam vacuum, hide-water wash and steam pasteurization (WLVHS) and irradiation showed the lowest CE ratios (5 and 2 for CE_P and 2.56 and 1.29 for CE_{CFU}, respectively).

In Figure 3.1.a the effectiveness of the decontamination measures (i.e. the reduction in prevalence of contaminated quarters) is plotted against the corresponding costs per quarter. The dashed line represents the least-cost frontier. The points located on the frontier are considered as the most cost-effective set of decontamination measures. For each measure under the frontier, there is at least one measure on the frontier which has either lower costs or higher effectiveness or both. For example, steam-pasteurization (S) and the combined set of hot-water wash and steam pasteurization (WS) have lower costs and higher effectiveness than ethanol-hide wash (H) that is located under the frontier. The least-cost frontier is made up by trim, steam-pasteurization, irradiation and the following combined sets: WS, WTS, WVS, WLTS, WLVS and WLVHS. Considering the 5th and 95th percentiles of the effectiveness, hot-water wash is the only measure located under the least-cost frontier.

In Figure 3.1.b the reduction in number of CFU on the surface of the meat caused by the different decontamination measures is plotted against the costs per quarter. The least-cost frontier is made up by trim, steam-pasteurization, ethanol-hide wash, irradiation and the combined set of WT. Considering the 5th and 95th percentiles of the effectiveness, hot-water wash, lactic-acid rinse, WS, WV, WTS, WVS and WLTS are located under the least-cost frontier.

Table 3.3. Cost-effectiveness ratio for decontamination measures and the combination sets

Decontamination measures and combination sets	Estimated quarter-level prevalence (%)		Estimated prevalence reduction (%)	Additional costs (€/quarter)	Cost-effectiveness ratio (ΔP/ ΔC), Yearly costs per 1% prevalence reduction (C/P) and ranking			Cost-effectiveness ratio (ΔlogCFU/ ΔC) [a] and ranking	
	Mean	5th, 95th percentiles	ΔP	ΔC	CE_P	ΔC/ΔP	Rank	CE_{CFU}	Rank
None (baseline scenario)	9.16	4.4, 13.1	0.00	0.00	-	-	-	-	
Carcass trim (T)	2.41	1.1, 3.6	6.75	0.22	31	16,340	1	14.	1
Carcass steam-pasteurization (S)	1.66	0.7, 2.5	7.50	0.30	25	20,233	2	11	2
Carcass steam-vacuum (V)	2.41	1.1, 3.6	6.75	0.35	19	26,452	3	9	4
Carcass lactic-acid rinse (L)	3.01	1.4, 4.4	6.15	0.36	17	29,236	4	8	7
WT	1.85	0.8, 2.8	7.31	0.44	17	30253	5	11	3
WS	1.20	0.5, 1.9	7.96	0.53	15	33,990	6	8	5
Carcass hot-water wash (W)	6.06	2.8, 8.8	3.10	0.22	14	35,758	7	3	13
WV	1.84	0.8, 2.9	7.32	0.57	13	39,535	8	6	8
WTS	0.32	0.1, 0.6	8.84	0.75	12	42,183	9	6	9
Hide wash with Ethanol (H)	1.98	0.9, 3.1	7.18	0.64	11	45,020	10	8	6
WVS	0.32	0.1, 0.6	8.84	0.87	10	49,904	11	4	10
WLTS	0.10	0.0, 0.3	9.06	1.11	8	61,000	12	4	12
WLVS	0.10	0.3, 0.3	9.06	1.23	7	68,537	13	4	11
WLVHS	0.02	0.0, 0.1	9.14	1.88	5	103,304	14	3	14
Irradiation (Ir)	0.02	0.0, 0.1	9.14	4.65	2	254,376	15	1	15

[a] ΔlogCFU is from Vosough Ahmadi et. al., (2006)

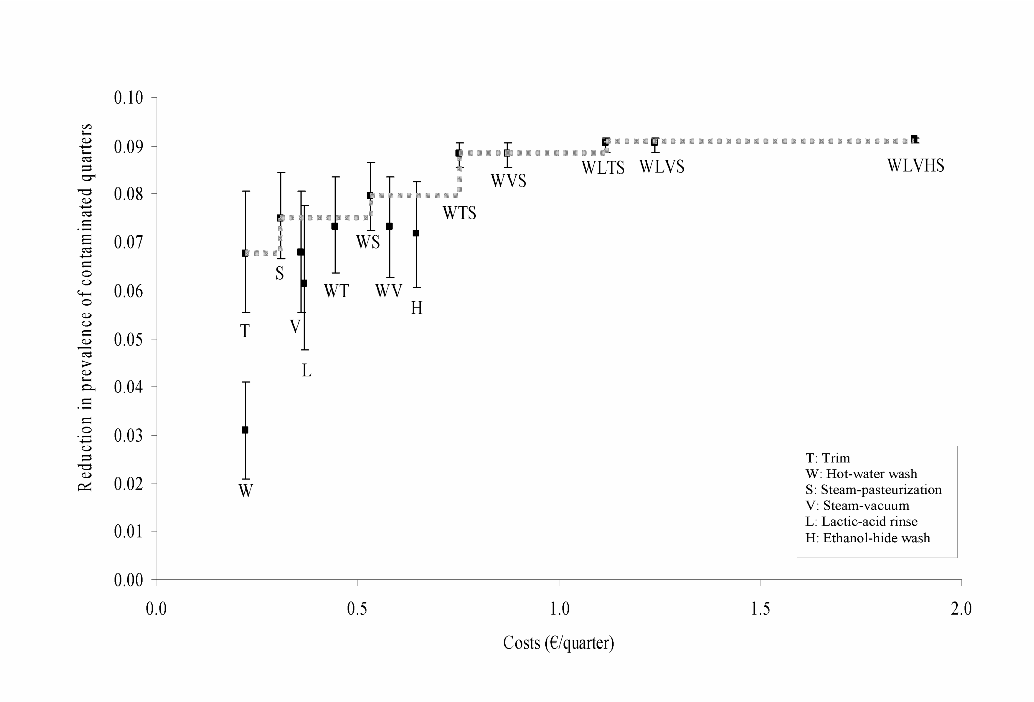

Figure 3.1.a. Least-cost frontier (…) of decontamination measures to reduce the average prevalence of VTEC O157-contaminated quarters. Given are the average reduction in prevalence (■) and the 5-95% confidence interval (I).

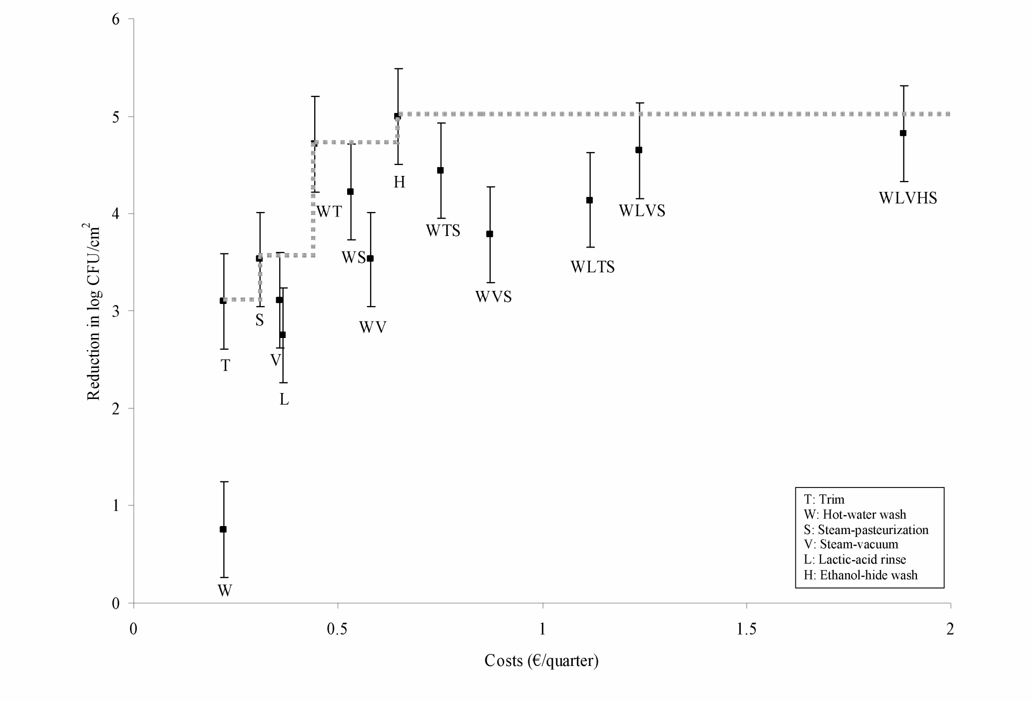

Figure 3.1.b. Least-cost frontier (…) of decontamination measures to reduce the average number of VTEC O157 (log CFU/cm^2) from the surface of the meat. Given are the average reduction in number of CFU (■) and the 5-95% confidence interval (I).

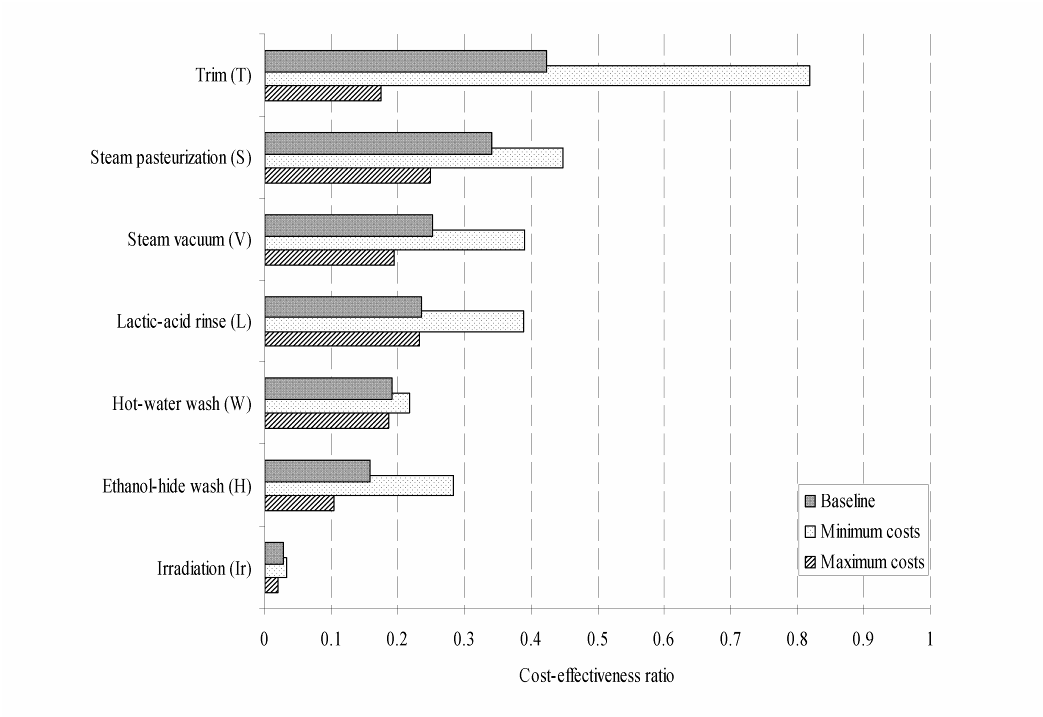

Figure 3.2.a. Comparison of the cost-effectiveness ratios of seven decontamination measures in the baseline scenario (using default input values) versus two scenarios of using minimum and maximum costs.

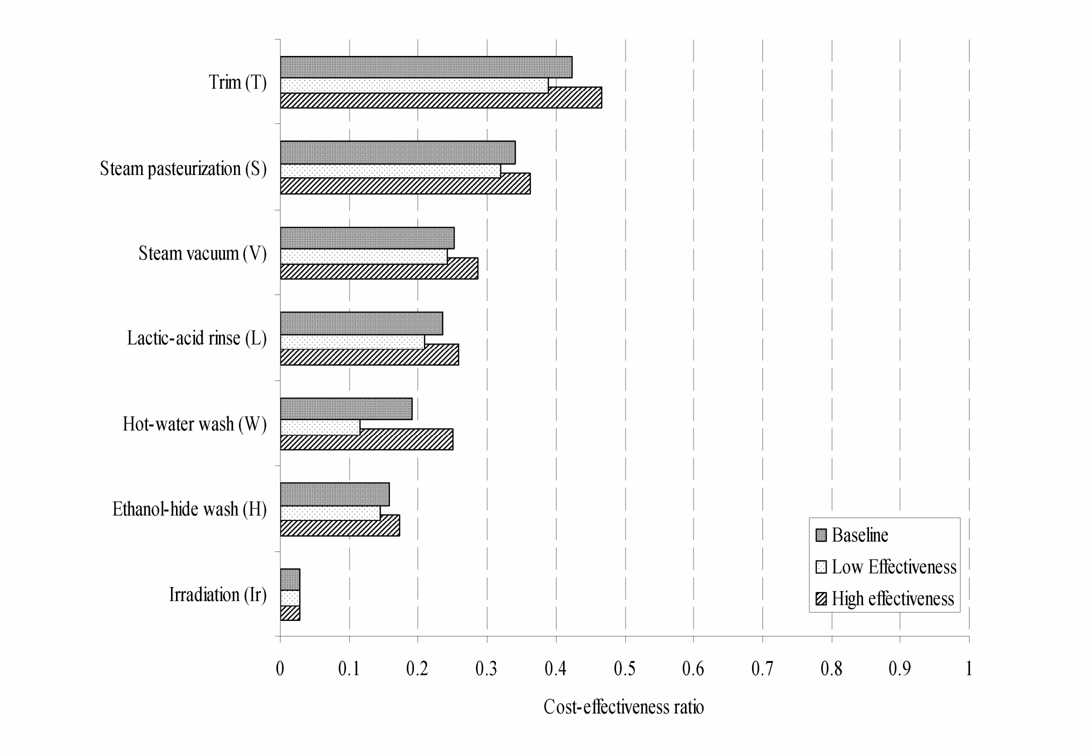

Figure 3.2.b. Comparison of the cost-effectiveness ratios of seven decontamination measures in the baseline scenario (using default input values) versus two scenarios of using low and high effectiveness (5^{th}-95^{th} percentiles).

In Figure 3.2.a it can be seen that to what extend the cost-effectiveness ratios (CE_P) of the seven decontamination measures change when the default values of the costs are changing (i.e., using the minimum and maximum values). This figure shows that the CE_P ratios of the measures and particularly trim are sensitive to the costs. Figure 3.2.b shows that to what extend the cost-effectiveness ratios (CE_P) are sensitive to the 5th and 95th percentiles of effectiveness. Only hot-water wash is slightly sensitive to the effectiveness, but the model outcomes for the other decontamination measures are relatively insensitive to changes in the level of the effectiveness.

4. DISCUSSION

The results from this study lead to the conclusion that in the Netherlands the cost-effectiveness (both CE_P and CE_{CFU}) of adding an additional trim station to the slaughterhouse is superior to the CE of the other decontamination measures and their combined sets. Trim is located on the least-cost frontiers that are shown in Figures 3.1.a and 3.1.b. The main reason is that trim incurs a lower level of costs and a relatively high level of effectiveness compared to the other alternatives. Trim's low cost level (€0.22/quarter) is mainly due to its low non-recurrent costs that are related to the fact that there is no need to invest in equipment. However, as a labour consuming measure it incurs recurrent costs. The sensitivity analysis showed that the CE_P of trim is very sensitive to costs, which is due to the high level of uncertainty on the number of workers needed to have an additional trim station along the slaughter line. According to Phebus et. al. (1997) the effectiveness of trim is a very uncertain parameter as well. Thus the highest ranking of the trim should be treated with care.

Our results showed that steam pasteurization is the second best option from the CE point of view. Steam pasteurization generates a lower total costs (€0.31/quarter) than lactic-acid rinse, steam vacuum, ethanol-hide wash and irradiation. Steam pasteurization is also located on the least-cost frontier for both CE_P and CE_{CFU}. These findings are in consistency with the results reported by Jensen et al. (1998) who found trim and steam pasteurization as the two most cost-effective decontamination measures to be applied in US slaughterhouses. However, the capacity of the considered slaughterhouse in that study was much higher than in our study (4,800 cattle versus 500) which resulted in relatively lower costs in US due to the scale effect.

Steam vacuum and lactic acid rinse are located in the third and fourth rank from the CE_P point of view and fourth and seven ranking from CE_{CFU} point of view. Despite these findings these decontamination measures are located under the least-cost frontier and therefore dominated by others. Similarly hot-water wash in both CE types, WT, WV and ethanol-hide wash in the CE_P least-cost frontier analysis and WS, WV, WTS, WVS, WLTS, WLVS and WLVHS in the CE_{CFU} least-cost frontier analysis are dominated by other decontamination measures on the frontiers. Although irradiation was not in Figures 3.1.a and 3.1.b, it is part of the least-cost frontier, due to the fact that it has the highest effectiveness. This fact indicates that considering only the CE ratio may lead us to non-optimal conclusions. Thus, combining CE ratio analysis with the least-cost frontier analysis provides a better insight in the most optimal decontamination measures. In general, choosing the most cost-effective decontamination method or a combined set depends on two important criteria: the minimum prevalence of contaminated quarters (minimum prevalence threshold) that decision makers want to reach to and, the maximum costs per quarter that they are willing to spend to achieve that reduction. If a decision maker aims for a certain prevalence reduction, a horizontal line can be drawn indicating that decontamination measures below the line are excluded from the list of possibilities. A vertical line is drawn when the decision maker aims at a certain value as the maximum costs, indicating that the decontamination measures on the right hand side of the frontier are not acceptable.

The estimated costs of decontamination measures are based on data coming from three experts of three industrial Dutch beef slaughterhouses. And estimating a realistic value for some inputs such as number of additional workers needed for certain decontamination measure was very difficult for the experts. Therefore, in some cases we applied uncertain but conservative estimates for both costs and effectiveness. However, the uncertainty involved in these data does not affect the ranking based on the CE_P,

A reduction in the prevalence of VTEC O157-contaminated quarters to 2% (i.e., 2% of the quarters are contaminated) due to implementing the decontamination measures is achieved at costs of €0.20 to €0.50 per quarter which is 16% to 40% of the estimated margin of the slaughter net profit per carcass, which is €5.00. A reduction of the prevalence to 1% (i.e., 1% of the quarters are contaminated) will cost at least €0.50 to €1.00 per quarter or €2 to €4 per carcass. This is 40% to 80% of the estimated net profit per carcass and incurs annual additional costs of €250,000 to €500,000 for the slaughterhouses. These costs obviously affect the net profit of the slaughter plants. Thus, their willingness to invest in decontamination measures to improve the level of beef safety depends on some other factors, which we did not include them in this study, such as: the degree of risk aversion, food-related outbreaks, live-animal purchase price and sell price of the meat as well as the food safety regulations. At this time, there is no market price incentive or other encouraging factor for the slaughterhouses to invest in decontamination measures that improves the VTEC O157-dependent beef-safety. However, occurrence of beef-borne outbreaks might push them to consider such investments. On the other hand because the supply of Dutch meat has decreased rapidly in the last few years, the industry has a scaling-up strategy (Piëst, 2004). To stay in the business and competition, companies (slaughterhouses) are taking over other companies in the industry to reduce the costs and to maintain their production. Because of these developments, in the last years the number of slaughterhouses has decreased but the size of the remaining plants has increased. In this situation these larger plants could be able to invest in the measures to improve the beef-safety level.

The results of the sensitivity analysis for the baseline output of the contaminated quarters at slaughterhouse showed that the output of the epidemiological model was sensitive to the environment of the slaughterhouse (Vosough Ahmadi et al., 2006b). Similarly, results showed that considering the uncertainty of the effectiveness of interventions, particularly of steam-pasteurization, steam-vacuum, trim and lactic-acid rinse, influence our ranking. Therefore, the uncertainty involved in the effectiveness level of the decontamination measures should not be overlooked.

We did not include the effects of decontamination measures on reducing the other pathogens such as salmonella and campylobacter. In fact, assigning all the considered effectiveness for VTEC O157 is not a valid assumption and as a result will end up with an underestimation of the total effectiveness to improve product safety.

In this study the benefits of applying decontaminations to the beef slaughterhouses were measures in terms of the reduction in prevalence of the contaminated end-product and the number of CFU on the meat surface. Alternatively, the benefit of implementing these measures can be estimated based on the reduction of the health costs to the society that is imposed by the infected people due to consuming contaminated beef. This aspect was not elaborated in this paper and can be considered for the future investigations.

Similarly, the effect of the increased product safety, due to the implementation of the studied decontamination measures, on the beef price was not included. In fact, the costs and benefits in this study were estimated to support decisions at the slaughterhouse level. However, extrapolating the estimated costs and benefits for the decontamination measures at the national level (i.e. multiplying the costs per carcass by the number of annually culled dairy-beef cattle) might be interpreted in a different way than in the current paper.

5. CONCLUSIONS

A reduction in the prevalence of VTEC O157-contaminated beef-carcass quarters to 2% can be achieved at costs of €0.20 to €0.50 per quarter which is 16% to 40% of the estimated margin of the slaughter net profit per carcass. A reduction to 1% will cost at least €0.50 to €1.00 per quarter. We showed that carcass trim and carcass steam-pasteurization can be considered to be the most cost-effective decontamination measures to be applied in a Dutch beef slaughterhouse to reduce the prevalence of VTEC O157-contaminated beef-carcass-quarters and CFU/cm^2 of the meat surface. Nevertheless, the lowest level of VTEC O157 prevalence (to less than 1%) will be achieved by implementing a combination set of decontamination measures that cost between €1.00 to €2.00 per quarter or by implementing irradiation which costs €4.65 per quarter.

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APPENDICES

Appendix 3.1. Values of additional items needed for decontamination measures.

Decontamination measures	Additional worker (person)			Equipment				Water (litre/h)	Electricity (kwh)	Gas (m^3/h)	Acid lactic & ethanol (litre/animal)
				Investment including installation (€×1,000)			Life-time/year				
	Min	Mode	Max	Min	Mode	Max					
Ethanol-hide wash (H)	2	3	3	5	10.5	15	7	-	10	-	4.8
Hot-water wash (W)	0	0	0	10	82	82	8	2,724	16.57	127	-
Lactic-acid rinse (L)	0	1	1	30	156	156	8	2,500	16.57	127	0.03
Steam-vacuum (V)	1	2	3	15	82	100	7	1,260	16.57	93	-
Trim (T)	1	2	5	12	18	30	2	-	-	-	-
Steam-pasteurization (S)	0.5	1	2	150	251	275	10	1,661	15.77	93	-
Irradiation (Ir)	-	4	-	-	-	-	-	-	-	-	-

Appendix 3.2. General and some specific parameters and their values used for cost calculation.

Item	Values and prices			Unit
	Minimum	Mode	Maximum	
Labour cost	22	25	36	€/ hour
Working hours	7	8	9	Hours
Working days	-	250	-	days/year
Interest rate [a]	0.01	0.04	0.07	%
Exchange rate [b]	-	0.819	-	($/€)
Lairage space	-	1.75	-	m^2/cattle
Lairage capacity		120		Cattle
Irradiation fee	0.03	0.04	0.06	€/kg
Water	-	0.0016	-	€/ litre
Electricity	-	0.0832	-	€/ Kwh
Natural Gas	-	0.3089	-	€/ m^3
Water refining	-	0.0004	-	€/ litre
Land lease	-	0.0450	-	€/ m^2/month
Ethanol	-	0.2600	-	€/ litre
Lactic Acid	-	2.0637	-	€/ litre
Meat transportation	-	250	-	€/ truck (2 ways)

[a] From de web site of de Nederlandsche Bank: http://www.dnb.nl
[b] From the website: http://www.ratesfx.com on November 2005

Chapter 4

Effectiveness of simulated interventions in reducing the estimated prevalence of *Escherichia coli* O157:H7 in lactating cows in dairy herds

Paper by Vosough Ahmadi B., Frankena K., Turner J., Velthuis A.G.J., Hogeveen H. and Huirne R.B.M. (2007), Veterinary Research. In press.

SUMMARY

A transmission model developed to investigate the dynamics of VTEC O157 bacteria in a typical Dutch dairy herd was used to assess the effectiveness of vaccination, diet modification, probiotics (colicin) and hygienic measures as to water troughs and bedding, when they are applied single or in combination, in reducing the prevalence of infected animals. The aim was to rank interventions based on their effectiveness in reducing the baseline prevalence of infected animals in the lactating group. The baseline prevalence of the lactating group and the within-herd prevalence were estimated by the model to be 5.02% and 13.96% respectively. Results showed that all four interventions, if applied to all four animal groups or only to young stock, are the most effective and will reduce the baseline prevalence by 84% to 99%. In general, combinations of hygiene (applied in all groups) and one other intervention have the highest effectiveness in reducing prevalence in the lactating group. Vaccination and diet modification showed a slightly higher effectiveness than colicin and hygiene.

1. INTRODUCTION

Escherichia coli O157:H7 (VTEC O157 in this paper) is one of hundreds of strains of the bacterium *Escherichia coli* that is found regularly in the faeces of healthy cattle (Besser et al., 1999; Chapman, 2000; Schouten et al., 2004). It can be transmitted to humans through direct contact with faeces and by consumption of contaminated beef and dairy products (Lesaux et al., 1993; Bell et al., 1994; Rodrigue et al., 1995; Coia, 1998). A human infection is associated with a wide range of symptoms, including asymptomatic shedding, non-bloody diarrhea and hemorrhagic colitis, life-threatening complications such as hemolytic-uremic syndrome (HUS), particularly in children under five years, thrombotic thrombocytopenic purpura (TTP) in elderly people, and death (Eklund et al., 2002). The incidence of human infection with VTEC O157 in the Netherlands is estimated to be 1,251 cases per year (Havelaar et al., 2004). The severe health consequences of human infection make preventive strategies important.

Dairy and beef cattle are known as the main reservoirs of VTEC O157 and the bacteria can be found at several locations on the farm including other animals, water, soil and feed. Beef is known as one of the main transmission vehicles to consumers. Interventions that reduce the risk of beef becoming contaminated with VTEC O157 can be applied at farm and transport level (i.e., pre-harvest interventions) and/or at slaughter and processing levels (i.e., post-harvest interventions). Reducing the number of infected lactating cows is a good approach in reducing the level of beef-borne human VTEC O157 infections, because a large proportion of the beef consumed in the Netherlands originates from (domestic) dairy cows culled and slaughtered.

Some farm attributes (e.g., water and sediments in water troughs) have been frequently reported as main on-farm risk factors for VTEC O157 transmission and based on that, appropriate bio-security interventions have been suggested (Collins and Wall, 2004). Also measures that reduce the concentration of VTEC O157 shed in the faeces of infected cattle, such as probiotics and vaccination, were identified as effective interventions (Callaway et al., 2004). However, little is known about the capability of these interventions in reducing the prevalence of infected animals in the beef producing group (i.e., lactating cows) as well as in the whole herd.

Understanding the transmission and survival process of food-borne pathogens in a highly managed and complex system, such as a modern dairy farm, requires a framework to cover all the aspects. Moreover, evaluating the interventions by direct implementation is often costly and interruptive of the routine farm practice. Thus, epidemiological models that simulate the dynamics of food-borne bacterial populations in a representative herd (e.g., VTEC O157 and *Salmonella* spp.) (Turner et al., 2003; Turner et al., 2006; Xiao et al., 2006) are important tools to estimate the effectiveness of interventions in the whole herd and in specific groups of animals (e.g., lactating group). In such a modelling approach, population dynamics of the concerned pathogens and the effect of management of the farmer on the dynamics are simulated using a combination of numerical and analytical techniques. Such models have shown to be useful in predicting the long term behaviour of food-borne pathogens, like *Salmonella* infections in livestock, and were used in the development of more effective intervention strategies (Xiao et al., 2005). Intervention strategies against VTEC O157 can be categorized into antibacterial, probacterial, dietary and management strategies (Callaway et al., 2004). In this study, based on literature, we selected one intervention from each of the categories mentioned which were: vaccination, probiotics (i.e., colicin), diet modification and more frequent replacing and cleaning bedding materials and water troughs.

The objective of this study was to rank interventions based on their effectiveness in reducing the baseline prevalence of infected animals in the lactating group and the baseline herd prevalence.

2. MATERIALS AND METHODS

2.1 General description of the model

A VTEC O157 transmission model that was developed to investigate the population dynamics of *E. coli* O157 in a typical UK dairy herd (Turner et al., 2003) was used to assess the effectiveness of four on-farm interventions in the Netherlands. Figure 4.1 represents the model structure. The four management groups in the model are young stock under-six-months old (U), young stock above-six-months old (A), dry (D) and lactating (L) adult cattle. Susceptible (X) and infected (Y) animals pass from the under-six-month group to the above-six-month with maturation rate of (g_i), then to the dry group and finally to the lactating group as they grow older. At the end of lactation animals re-enter the dry group and this cycle continues (parameters c and d in the model) until lactating animals are culled (denoted by m). Besides that, an animal death rate was included in the model for each group (denoted by b_i, i indicating the group).

Within each group i direct host-to-host transmission occurs and susceptible animals move to the infectious group with rate β_i and recover with rate γ_i. Infected animals (Y_i) shed infectious doses (η_i) (it is assumed that 100 colony forming units (CFU) represent one infectious dose) into their group-specific environments (E_i) during their infectious period (Turner et al., 2003).

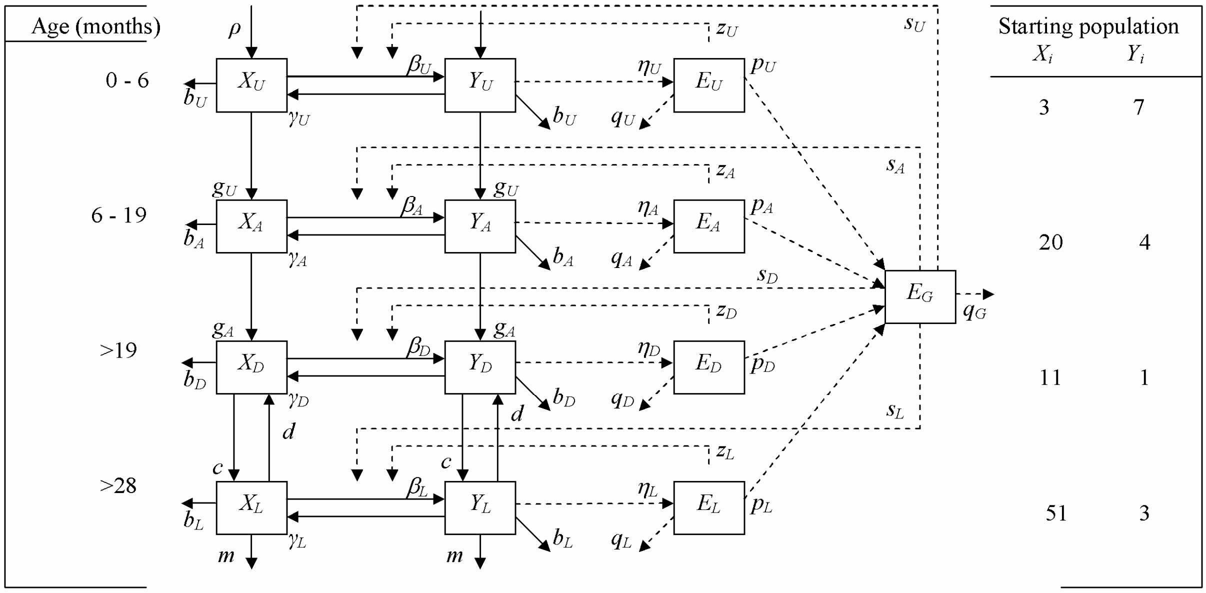

Figure 4.1. Schematic overview of the model and the relationships modelled between the groups and general and specific environments.

The term 'infected' is used to denote animals that shed more bacteria than they initially ingested, as a result of colonization. Therefore, an animal that sheds bacteria, without amplification of the number of bacteria, was considered to be of little importance. Animals do not gain immunity, so when shedding stops they return to the susceptible group. There is a flow of bacteria from each group-specific environment to the 'general' environment (E_G) that poses a risk to all groups, which is expressed in the pooling rate (p_i). The general environment represents personnel or equipment that routinely come into contact with the various groups and provides a route of transmission between all groups. Susceptible animals can become infected by ingesting infectious units from either their group-specific environment (represented by the group-specific environment indirect-transmission parameter z_i), perhaps from contaminated bedding, feed and water troughs, or from the general environment (represented by general environment indirect-transmission parameter s_i). A daily death rate (q_i) of bacteria was incorporated in the model for both the group-specific and general environment. This represents natural bacterial elimination or the effect of any bactericidal intervention (e.g., cleaning water troughs or changing/cleaning the bedding material). The model also includes pseudovertical transmission (ρ, representing transmission from dam to calf within the first hours after birth).

The model was run for a period of 1,000 days with an infected condition (i.e., the number of infected animals were 7, 4, 1, and 3 in U, A, D and L groups respectively; these numbers originated from the equilibrium situation, that is when the proportion of infected animals becomes constant, after introducing one infected animal to a negative herd) at start. The total number of animals in the herd remained constant. The exchange of animals between susceptible and infectious groups was calculated using differential equations. Also two transition matrices were used to calculate the time spent in each group and each environment. For details of the differential equations and matrices see Turner et al. (2003).

2.2 Input

Table 4.1 and the first column of Table 4.2 represent the values of the input parameters. There are three categories of input variables in the model. The first category is related to the general dairy-farm management such as total herd size (N), maturation rate (g_i) of the animals, rate of flow from dry to lactating (c) and vice versa (d). Values used for these parameters were according to Dutch dairy practice. The average total herd size in the Netherlands was estimated to be 100 (CBS, 2005), and the average milking period, dry period and maturation age were reported to be 345, 60 and 745 days respectively (NRS, 2005). The second category consists of the direct-transmission rates of VTEC O157 from animal to animal (β_i) in the various groups. No Dutch specific data were available for these parameters. Turner et al. (Turner et al., 2003) assumed values for these parameters that were updated in their more recent paper (Turner et al., 2006). The latter parameter values were used in our study. The third category includes the group-specific (z_i) and general (s_i) indirect-transmission parameters, faecal-shedding rate (η_i), recovery rate (γ_i) and death rate (q_i) of pathogen. η_i, γ_i and q_i were deemed to be affected by intervention measures (see next section). Transmission parameters were considered density-dependent and their values were calculated for a herd size of 100.

2.3 Interventions

Two selection criteria for interventions were applied: (i) interventions should be effective according to the literature and (ii) quantitative data of their impact on the models' input parameters should be available. In this way, four interventions were considered: vaccination, modified diet in reducing the concentration of bacteria in the gastrointestinal tract, adding probiotics (colicin) to the diet, and application of better hygienic measures, consisting of more frequent cleaning of water troughs and replacement of bedding material. Three of the input parameters (η_i , γ_i and q_i) can be affected by these interventions. The faecal shedding rate η_i is the product of the bacterial concentration K_i (i.e., CFU/g) and the quantity of faeces produced per day. Vaccination affects both faecal shedding and the recovery rate. However, diet modification and colicin affect only the shedding rate. Hygiene only affects the pathogen death rate (q_i). Table 4.2 shows the values of the input parameters affected. Details of the selected interventions are described in the following sections.

2.3.1 Vaccination

A substantial amount of research was carried out to develop new vaccines against VTEC O157 (Conlan et al., 1999a; Conlan et al., 1999b; Conlan et al., 2000; Potter et al., 2004). Potter et al. (Potter et al., 2004) describes a recently developed vaccine, which was successfully tested in an experimental study. This vaccine raises antibodies that interfere with gut colonisation of the host (cattle or other hosts) by VTEC O157. In a trial, 3 doses of the vaccine were administered at 3-week intervals during 106 days. Results showed a 10-fold reduction in log number of CFU bacteria/gram of faeces of calves and yearlings. The shedding duration was at maximum 11 days for the vaccinated groups. This implies a higher recovery rate for young stock (i.e., under-six-months old (U) and above-six-months old (A) groups) and a slightly lower recovery rate for dry and lactating groups. We used these experimental data as the effect of the vaccine mentioned in this study and we called it vaccine (a). Vaccine (b) is an imaginary type of the vaccine that produces a 10-fold reduction in the shedding rate without affecting the recovery rate. We used vaccine (b) to evaluate the sensitivity of the model to recovery rate.

2.3.2 Diet modification

Diet and feeding practices are considered to be important factors affecting faecal shedding of VTEC O157. Diets containing high forage or high grain are mentioned in the literature as influential factors. In an experimental study, the effect of four feed rations, namely high-forage no-monensin (HFNM), high-forage with-monensin (HFM), high-grain no-monensin (HGNM) and high-grain with-monensin (HGM), on the number of bacteria shed as well as the effects on the shedding duration (recovery rate) were studied (Van Baale et al., 2004). Monensin is used in some countries to increase milk production, to improve feed efficiency and to control ketosis and bloat. Because all the rations mentioned reduced the shedding rate to below the detection level after a period of time (between 19 and 68 days), we assumed that the concentration of bacteria in faeces will be below the detection level by switching from the normal diet to these modified diets. Because the baseline values of the recovery rates used in the model were very close to the recovery rates observed in the experimental study (Van Baale et al., 2004), the baseline values were used.

Table 4.1. Input parameters and values that were not affected by interventions.

Parameter		Unit	Value	Parameter		Unit	Value
N	Total herd size	animal	100	η	Shedding rate	units/day	
ρ	Pseudovertical transmission		0.46		η_U, η_A, η_D, η_L		$k_i \times f_i \times 10$
g	Maturation rate	animal/day		p	Pooling rate	units/day	
	g_U		0.00556		p_U, p_A, p_D, p_L		0.00025
	g_A		0.00178	β	Direct tr.	per animal/day	
c	Flow from dry to lactating	animal/day	0.0166		β_U		0.0256
d	Flow from lactating to dry	animal/day	0.0029		β_A		0.0013
b	Death rate	animal/day			β_D		0.0034
	b_U		0.000137		β_L		0.0009
	b_A		0.000023	z	G-specific indirect-tr	per animal/day	
	b_D		0.000046		z_U		2.132×10^{-10}
	b_L		0.000046		z_A		4.681×10^{-12}
m	Culling rate	animal/day	0.0008		z_D		1.652×10^{-8}
					z_L		1.484×10^{-8}
f	Faecal shedding	kg/day		s	General indirect tr	per animal/day	
	f_U		4.9		s_U		$0.01z_U$
	f_A		12.6		s_A		$0.005z_W$
	f_D and f_L		37.1		s_D		$0.01z_D$
					s_L		$0.02z_L$

Table 4.2. Input parameters and values that were affected by interventions.

Parameter		Unit	Baseline	With-intervention				
				Vaccine (a)	Vaccine (b)	Diet modification[b]	Colicin	Hygiene[c]
γ	Recovery rate	animal/day						
	γ_U and γ_A		0.068	0.090	0.068	0.068	0.068	-
	γ_D & γ_L		0.106	0.090	0.106	0.106	0.106	-
k	Concentration	CFU/g						-
	k_U and k_A		3.367×10^5	0.0	3.367×10^4	0.0	2.439×10^4	-
	k_D and k_L		7.0×10^1	0.0	7.0	0.0	5.07	-
q	Death rate of organism	units/day						
	q_U, q_A, q_D		0.1395	-[a]	-		-	0.631
	q_G		0.1395	-	-		-	0.139
	q_L		0.5075	-	-		-	0.631

[a] '-' means there was no change

[b] consists of HFNM (high-forage no-monensin), HFM (high-forage, plus monensin), HGNM (high-grain no-monensin) and HGM (high-grain plus monensin).

[c] hygiene consist of replacement of bedding (*q*: 046) and cleaning water troughs (*q*: 0.169).

2.3.3 Probiotics

Probiotics or competitive exclusions (CE) are capable of reducing pathogenic microorganisms in livestock (Zhao et al., 1998; Brashears et al., 2003; Schamberger and Diez-Gonzalez, 2004; Schamberger et al., 2004). The ability of colicinogenic *E. coli* that produce colicin E7 (DNase) in reducing the prevalence of VTEC O157 in cattle has been investigated (Schamberger et al., 2004). Young cattle were infected with high doses of VTEC O157 and colicinogenic *E. coli* was added to the diet to produce colicin. In the treated group an average 1.14 log CFU reduction of bacteria per gram of faeces could be observed. Based on these results we considered a 1.14 log CFU reduction of bacteria shed by administration of colicinogenic *E.coli* to cows. Because the length of the reference study (Schamberger et al., 2004) was the same for treated and control groups (24 days), and both groups were positive in faeces to the end of the study, we assumed that there is no change in the shedding period and consequently the recovery rate in the model.

2.3.4 Hygiene

Hygienic measures affect daily death rate (q_i) of the pathogen in the group-specific environment and the general environment on a dairy farm. An exponential decay rate can be used in modelling the death of the bacteria outside the host (e.g., in faeces). In this model, we chose to incorporate the additional loss due to removal of faeces by increasing the baseline exponential decay rate. For simplicity we assumed that this parameter depends on two factors: (i) contaminated bedding and (ii) contaminated water troughs. The total effect of increasing the frequency of bedding replacement/cleaning and water trough cleaning is considered a hygienic measure in reducing the prevalence of VTEC O157 infected animals. The data of Scott et al. (Scott et al., 2006) and Davis et al. (Davis et al., 2005) were used to determine the bacterial death rate in water and bedding materials respectively, using formula 1:

$$C = \mathrm{I}e^{-q\gamma} \qquad (1)$$

where C is the number of CFU bacteria per millilitre of water or per gram of bedding, e is the base of natural logarithm, I is intercept or initial number of bacteria, q is the reduction rate and γ is the time scale. Using formula 1, we estimated that increasing the frequency of replacing bedding (in a straw yard housing system) or cleaning (in a cubicle housing system) from one to two times per week results in a death rate of 0.46 infectious units per day. This was done by fitting an exponential distribution to the data (i.e., initial number of CFU in the environment corresponding to the time unit (day) of the study) reported by Davis et al.(2005).

Following the same procedure and using the data obtained by Scott et al.(2006), it was estimated that increasing the frequency of cleaning the water troughs from once per month to four times per month results in a death rate of 0.17 infectious units per day. The parameter *q* in the model is assumed to relate to both water and bedding. Therefore, by increasing the cleaning or replacing frequency, the death rate will increase. Thus, the total death rate will be 0.63 infectious units per day, due to both interventions.

2.3.5 Combination of interventions

A combination of two or more pre-harvest interventions can also be applied in practice. However, some of the interventions considered in the model exert an effect on the same input parameters of the model (e.g., shedding rate is affected by vaccination, diet modification and colicin) and therefore determining the combined effect of two or more interventions on one input parameter is very difficult. Thus, combinations of hygiene and one of the other three interventions were examined. We assumed that improved hygiene is applied in all groups (U, A, D and L) when it is combined with other interventions. The model was run using single interventions (i.e., using only one intervention in one or more animal groups) and combinations of hygiene with other interventions (i.e., hygiene was applied in all animal groups and other interventions were applied in one or more animal groups).

2.4 Output

Prevalences within the lactating-group (P_{lact}) and the herd (P_{herd}) were the model's output of interest. The effectiveness of interventions is defined as the relative change of P_{lact} and P_{herd} from the baseline. Thus, the effectiveness was measured as:

$$Eff_{lact} = \left(BP_{lact} - P_{lact}\right) / BP_{lact} \; ; \; Eff_{herd} = \left(BP_{herd} - P_{herd}\right) / BP_{herd} \qquad (2)$$

Where Eff_{lact} and Eff_{herd} denote the effectiveness in the lactating group and herd and BP_{lact} and BP_{herd} denote the baseline outputs (they are the prevalences without any intervention) of the model.

2.5 Sensitivity analysis

The robustness of the outputs was examined by changing the following input parameters: direct transmission parameter (β_i), group-specific indirect transmission parameter (z_i) and the herd size (N). We changed only one of the parameters at a time. For direct transmission parameter and group-specific indirect transmission parameter ±10-fold of the default input values were examined, while for the herd size a minimum value of 75 and a maximum value of 125 were examined.

3. RESULTS

3.1 Baseline prevalence and with-intervention prevalence

The model was run for 1,000 days for without- and with-intervention situations. The baseline lactating group prevalence and herd prevalence were 5.02% and 13.96% respectively. The results of implementing the four studied interventions and the combination of hygiene with vaccination (a) are presented in Table 4.3.

Table 4.3 shows that, hygiene is most effective if it is applied to the whole herd (i.e., all animal groups) or to young stock (above and under-six-months old groups; U+A). Application of hygiene in the above-six-months old group plus lactating group (A+L) is more effective in reducing the P_{lact} than hygiene in only one of the groups or only in the adult groups of cows (D+L). The highest effect of hygiene on P_{herd} is achieved when it is applied in all the groups (U+A+D+L, ΔP_{herd}: 46.6%), although the same effect is obtained when implemented only to young stock groups (U+A, ΔP_{herd}: 45.3%).

Table 4.3. Relative reduction of lactating-group prevalence (P_{lact}) and herd prevalence (P_{herd}) from the baseline prevalences (baseline lactating-group prevalence was 5.02% and baseline herd prevalence was 13.96%) by implementing hygiene, vaccination (a) and vaccination (b), implementing diet modification and implementing colicin in various groups.

Interventions and implemented groups [a]	ΔP_{lact} (%)	ΔP_{herd} (%)	Interventions and implemented groups [a]	ΔP_{lact} (%)	ΔP_{herd} (%)
Additional hygiene			*Diet modification*		
U+A+D+L	89.6	46.6	U+A+D+L	99.6	54.6
U+A	84.4	45.3	U+A	98.9	54.3
A+L	62.1	32.6	A+L	84.0	39.1
A	48.7	29.9	D+L	63.2	14.0
U	30.1	14.9	L	61.7	12.6
D+L	25.3	6.3	A	53.7	32.7
L	22.3	4.5	U	39.4	21.8
D	3.7	1.9	D	4.1	2.2
Vaccination (a)			*Colicin*		
U+A+D+L	99.9	63.8	U+A+D+L	98.5	52.3
U+A	99.3	63.6	U+A	94.4	51.4
A+L	78.8	40.8	A+L	82.9	38.3
A	53.5	35.6	D+L	61.3	13.6
D+L	50.2	11.1	L	59.8	12.2
L	48.7	10.0	A	52.0	31.9
U	43.5	31.0	U	36.1	19.3
D	3.0	1.6	D	4.1	2.8
Vaccination (b)			*Additional hygiene plus vaccination (a)* [b]		
U+A+D+L	97.8	51.4	U+A+D+L	99.9	63.8
U+A	92.6	50.2	U+A	99.6	63.8
A+L	82.2	37.9	A+L	95.9	52.0
D+L	60.6	13.4	A	92.9	51.4
L	59.1	12.0	D+L	93.7	47.4
A	51.3	31.6	L	93.7	47.4
U	34.9	18.4	U	97.0	60.0
D	4.1	2.2	D	89.6	46.6

[a] U: under-six-month age group; A: above-six-month age group; D: dry group; L: lactating group.
[b] Additional hygiene was applied to all groups (i.e., whole farm) and vaccination (a) was applied to single and combined groups.

Results in Table 4.3 show that vaccination (a) has the highest efficacy in reducing P_{lact} when implemented in all the animal groups (i.e., U+A+D+L, ΔP_{lact}: 99.9%) or when implemented to young stock only (i.e., U+A, ΔP_{lact}: 99.3%). Vaccination (a) applied in the above-six-months old group plus lactating group (A+L) has a lower effectiveness (78.8%) in reducing the lactating group prevalence. Vaccination (a) applied in other groups such as above-six-months old group (A), adult groups (D+L), lactating group (L,) under-six-months old (U) and dry group (D) has a relatively low effectiveness in reducing P_{lact} (< 54%). The highest effect of vaccination (a) on P_{herd} is when it is implemented in all groups or in young stock only (ΔP_{herd}: 63.8%). Vaccination (a) when it is applied only in under-six-months old (U) group shows a relatively high reduction in P_{herd} (ΔP_{herd}: 31%) compared to its application in adults (D+L), lactating (L) and dry (D) groups. Also combination of vaccine (a) in under-six-months old (U) group and hygiene in the whole herd shows a 60% reduction in P_{herd}.

Vaccination (b) shows a slightly lower effectiveness than vaccination (a), indicating that a shorter shedding period has an effect on the effectiveness of the vaccine in reducing the prevalence. Table 4.3 shows that, similar to vaccine (a), using vaccine (b) in all groups has the highest effectiveness (97.8%) and using it in young stock (U+A) has the second best effectiveness. Vaccine (b) in above-six-months old plus lactating groups (A+L) and in adult groups (D+L) show 82.2% and 60.6% effectiveness. In general, vaccine (a) reduces the shedding period for groups U and A, but actually increases slightly the shedding period for groups D and L. Also, vaccine (b) differs from vaccine (a) in two ways. Vaccine (b) could be less effective just because it does not reduce the shedding rate as much as vaccine (a). However, it is probably a combination of both factors that leads to vaccine (b) being less effective than vaccine (a).

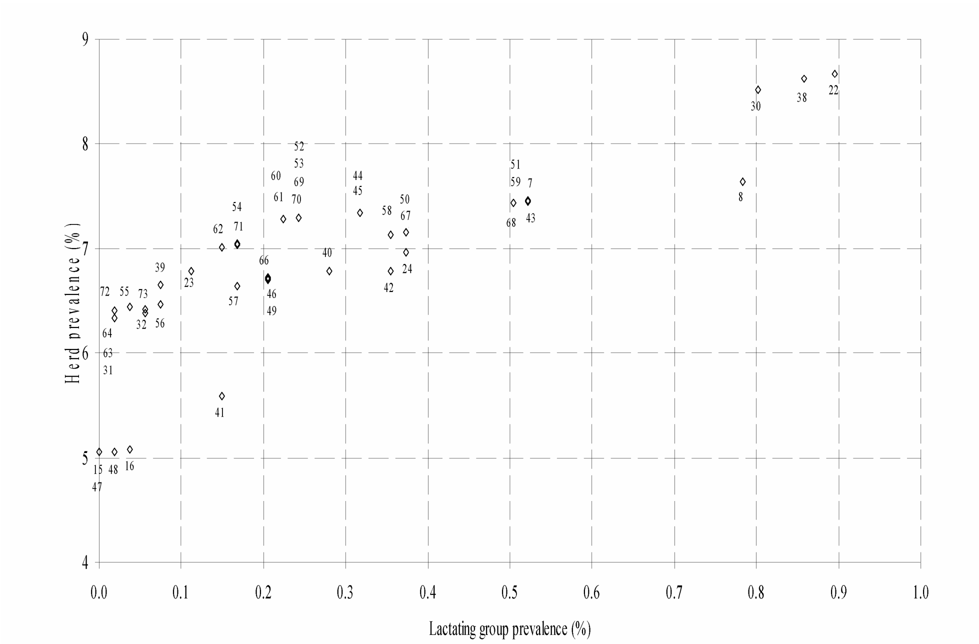

Figure 4.2. The reduction in lactating group prevalence on the horizontal axis is graphed against the reduction in herd prevalence on the vertical axis. Given are the interventions that were able in reducing the P_{lact} to <1% and P_{herd} to <9%. Each number corresponds to a particular intervention strategy, as described in Appendix 4.1.

Feeding a modified diet to the lactating group shows 61.7% effectiveness to P_{lact}. This is very close to the effect (63.2%) of feeding modified diet to all adult animals of the farm (D+L). However, the effects on P_{herd} are low (14.0% and 12.6%). Feeding a modified diet is most effective when it is fed to all the groups or to young stock (U+A) (99%).

Colicin reduces the P_{lact} by 59.8% when it is applied in the lactating group only. Its effect on P_{herd} is slightly higher than vaccination (a) and (b).

In Figures 4.2 and 4.3, the reduction in lactating group prevalence on the horizontal axis is graphed against the reduction in herd prevalence on the vertical axis. Figure 4.2 illustrates the interventions that were able in reducing the P_{lact} to <1% and P_{herd} to <9%. This Figure represents interventions that are best in reducing both P_{lact} and P_{herd}. Each number corresponds to a particular intervention strategy, as described in Appendix 4.1. The majority of the best interventions are a combination of hygiene with other interventions. However, there are some exceptions. Vaccination (a) in all groups (15) and vaccination (a) in U+A (16) are single interventions that effectively reduce both P_{lact} and P_{herd}. Modified diet in U+A (32), vaccination (b) in all groups (23) and colicin in all groups (39) are other single interventions that are effective in reducing P_{lact} by >98% and to a lower extent P_{herd}. Implementing hygiene in all groups (7) as well as implementing it in young stock only (8) shows a relatively good effectiveness in reducing P_{lact} by almost >90%.

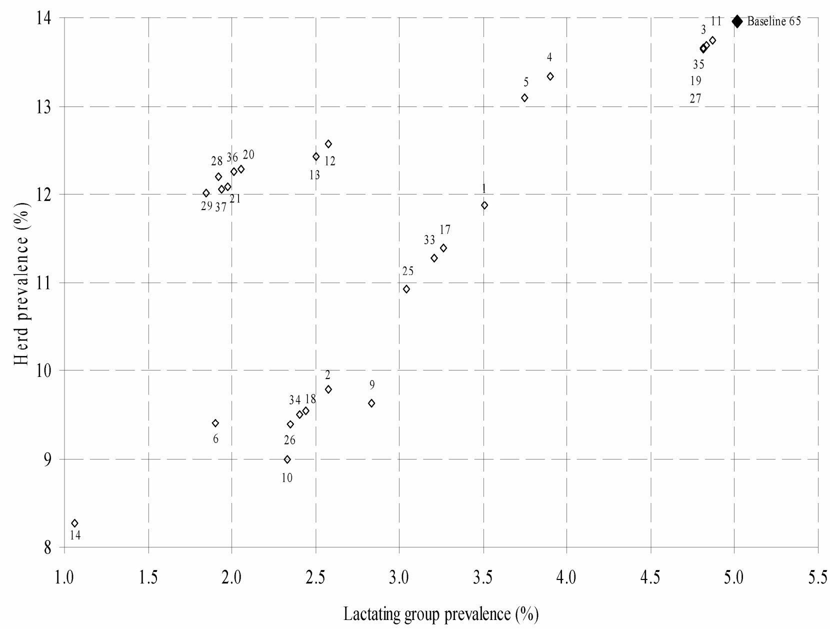

Figure 4.3. The reduction in lactating group prevalence on the horizontal axis is graphed against the reduction in herd prevalence on the vertical axis. Given are the interventions that were able in reducing P_{lact} from >1% to <5.02% (i.e., baseline) and, in reducing P_{herd} from >8% to <13.96% (i.e., baseline). Each number corresponds to a particular intervention strategy, as described in Appendix 4.1.

Figure 4.3 illustrates the interventions that were able in reducing P_{lact} from >1% to <5.02% (i.e., baseline) and, in reducing P_{herd} from >8% to <13.96% (i.e., baseline). None of the combined interventions falls under these limits. The best intervention in this figure in reducing both P_{lact} and P_{herd} is vaccination (a) in above-six-months old group plus lactating group (A+L) (14). Hygiene in above-six-months old group plus lactating group (A+L) (6) is the second best intervention in this figure. In general, the application of hygienic measures shows a lower effect on P_{herd} than the effect of the other interventions (see Table 4.3).
According to Figure 4.2, the top ten interventions in reducing P_{lact} were 15, 47, 48, 16, 31, 63, 64, 72, 55 and 32. These interventions reduce P_{lact} to a value <0.1%. These interventions were either single interventions in all groups, only in young stock groups or as a result of a combination of hygiene in all groups and other interventions.

3.2 Sensitivity analysis

Figure 4.4 shows the result of the sensitivity analysis for the three input parameters of the model. The lactating group prevalence is very sensitive to direct transmission parameters as well as group-specific indirect transmission parameters. However, it is not sensitive to the herd size. The results of the sensitivity analysis of the herd prevalence showed the same pattern of sensitivity to the direct transmission parameter and group-specific transmission parameter.

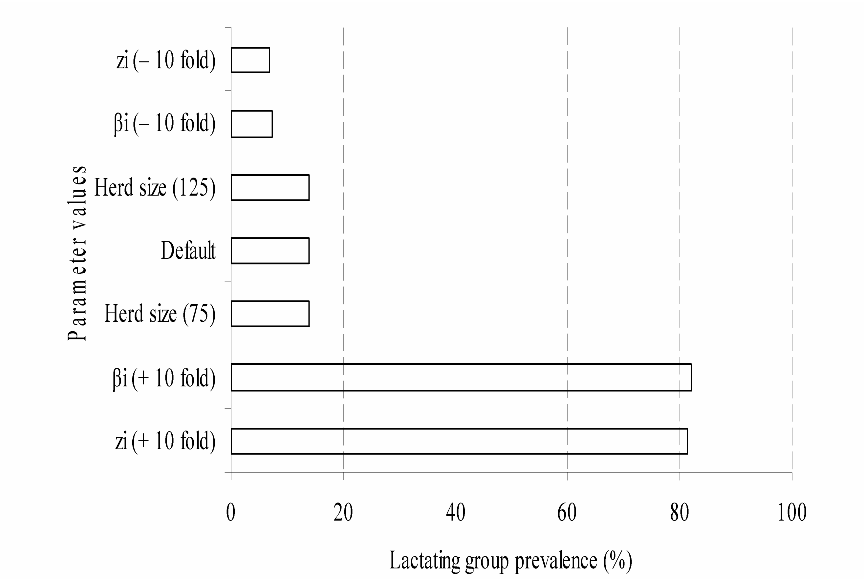

Figure 4.4. Results of the sensitivity analysis of the impact of the three input parameters of the model, which were not affected by the interventions. Given are the estimated prevalences in lactating group. For direct transmission parameter (β_i) and group-specific indirect transmission parameter (z_i) ±10-fold of the default input values were examined, while for herd size a minimum value of 75 and a maximum value of 125 were examined.

4. DISCUSSION

In this study we evaluated the effectiveness of four interventions in reducing the prevalence of VTEC O157 in either the lactating group or the whole dairy herd, using a deterministic transmission model and quantitative input data. The deterministic essence of the model cannot capture the spontaneous fade-out of the infection that is possible in reality. The parameters related to indirect-transmission parameters (i.e., shedding rate, animals' recovery rate and pathogen death rate) were assumed to be affected by the interventions considered in this study.

However, the direct-transmission parameters might also be affected by the interventions, but this was not included in this study, mainly due to the lack of quantitative data. On the other hand, the results of the sensitivity analysis showed that the output is very sensitive to the direct-transmission parameters. Therefore, the effectiveness of interventions might have been underestimated. Our current knowledge about the direct-transmission parameters is limited. Therefore, field studies are recommended to obtain reliable estimates for these parameters. Also, splitting the herd into 2 groups of young stock and 2 groups of adults is a simplification of the real Dutch dairy farming system that in many cases consists of more than four groups of young stock. This fact increases the number of transmission routes of the pathogen between the groups and its inclusion in epidemiological models requires much more precise field data, which are lacking.

The baseline lactating group prevalence and herd prevalence were estimated by the model to be 5.02% and 13.96% respectively. These figures are close to the real prevalence estimations. The real lactating group prevalence was estimated to be 2.2% to 10.7% (Heuvelink et al., 1998). The same study estimated the real herd prevalence to be 0.8% to 22.4% in the Netherlands. Implementing vaccination, diet modification and colicin in all animal groups or only in young stock are all effective interventions in reducing the baseline P_{lact} by >90%. This is in accordance with the literature (Turner et al., 2003; Potter et al., 2004; Schamberger et al., 2004; Van Baale et al., 2004). Previous studies (Turner et al., 2003; Turner et al., 2006) show that implementing on-farm interventions in the entire animal groups of the farm (U+A+D+L) or only in young stock groups (U+A) are the most effective interventions when targeting at P_{lact}. One reason for this could be that the number of bacteria shed by young stock is higher than by adult cattle and interventions considered here mainly affect this parameter. Implementing hygiene only in all groups or in young stock reduces P_{lact} by 89% and 84%, respectively. This is less effective than the other three interventions, but still is a noticeable reduction in P_{lact}. Given the fact that hygiene, (i.e., cleaning water troughs and replacing/cleaning bedding materials more frequently), only affects the bacterial death/removal rate and not the shedding rate, it can be considered a simple and easy-to-apply method. Moreover, a combination of implementing hygiene in all groups and application of one of the other three interventions in one or more animal groups is very effective (>89% reduction in prevalence).

The results also indicate that implementing diet modification, colicin and vaccination (b) in group L is slightly more effective than implementing them only in the above-six-month old young stock groups (59%-61% versus 51%-53%). This is inconsistent with the finding of Turner et. al.(Turner et al., 2006) that suggests that the best approach to decrease P_{lact} is in reducing the shedding rate and the shedding period in the young stock group (weaned group in their study). One reason for this discrepancy might be that we used Dutch specific input parameters, particularly for the dairy practice parameters instead of UK specific values. There are differences between the two countries values mainly in maturation rate, flow from dry to lactating groups and vice versa as well as culling rate. Nevertheless our findings show that the best target group in reducing the herd prevalence (P_{herd}) is the young stock above six-month old group (A), which is consistent with the findings of Turner et al. (Turner et al., 2006) under UK conditions.

In our reference study (Van Baale et al., 2004) for diet modification, a combination of high forage/high grain with monensin was used. In principle, use of ionospheres such as monensin is prohibited in the Netherlands. However, we included it as a potential intervention that might be considered in the future. Also, both diets evaluated by Van Baale et al. (2004) are not a commonly used in the Netherlands. Because there has not been a specific Dutch study on reducing the shedding concentration via diet modification, we used the results of the above study as our basis. It is clear that switching the current routine diet on the Dutch dairy farms to the diets used in this study will be interruptive and costly. Therefore, until having a specific Dutch experimental study of the effect of diet modification on the concentration of VTEC O157 shed, diet modification cannot be strongly advised for practice. Moreover, we assumed that the new diet reduces only the shedding rate as a result of hindering colonization of the bacteria in GI tract. However, we might expect that the duration of shedding and consequently recovery period are reduced also. This was not included in the model to avoid adding complexity by using uncertain data or making more assumptions.

Probiotics and mainly colicin are mentioned as effective interventions to control VTEC O157 at farm level (Schamberger et al., 2004). However, our results show that colicin is only effective when it is administered at least in above six-month old group (A) and under six-month old group (U). This is most probably due to the fact that the recovery period of the animals in the study by Shamberger et al. (2004) was longer than the default value used in the model.

Results show that implementing the hygienic intervention in young stock plus lactating groups (A+L) has closely the same effect as implementing modified diet in group L. Thus, the decision about which intervention should also take implementation costs into account.

Selecting the best intervention and the best target group will still depend on the result of a cost-effectiveness analysis as well as a utility analysis of the decision makers in the field. We therefore recommend that first, conditions and limitations of the modelling approach should be considered when interpreting these results and second, further field studies should be done to prove the assumptions and to assess the cost-effectiveness of the on-farm interventions.

5. CONCLUSIONS

The objective of this paper was to rank simulated interventions based on their effectiveness in reducing the baseline prevalence of infected animals in the group of lactating-dairy cattle. The first conclusion is that combinations of hygiene in all groups and one other intervention are in the top ranking of interventions in reducing the lactating group prevalence and to a lower extent the herd prevalence. The second conclusion is that implementing each four single interventions studied in all the animal groups of the farm (whole herd) or only in young stock groups are the second top ranking interventions. The third conclusion is that vaccination, diet modification and colicin E7 are estimated to be more effective than hygiene in reducing P_{lact} given our assumptions used in this study. Results showed that in some cases single interventions are as effective as combined sets. The result of this paper gives an insight into the interventions that can be considered for implementation. It also shows that field data are still lacking that could enable an even better judgement on the effectiveness of interventions.

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APENDIX 4.1

Numbers related to interventions and implemented groups mentioned in Figure 4.2 and Figure 4.3

#	Intervention - group	#	Intervention - group	#	Intervention - group	#	Intervention - group
1	Hygiene - U	20	Vaccine (b) - L	39	Colicin - U+A+D+L	58	Hyg. & diet - A
2	Hygiene - A	21	Vaccine (b) - D+L	40	Colicin - UA	59	Hyg. & diet - D
3	Hygiene - D	22	Vaccine (b) - A+L	41	Hyg. & vacc. (a) - U	60	Hyg. & diet - L
4	Hygiene - L	23	Vaccine (b) - U+A+D+L	42	Hyg. & vacc. (a) - A	61	Hyg. & diet - D+L
5	Hygiene - D+L	24	Vaccine (b) - U+A	43	Hyg. & vacc. (a) - D	62	Hyg. & diet - A+L
6	Hygiene - A+L	25	Diet - U	44	Hyg. & vacc. (a) - L	63	Hyg. & diet - U+A+D+L
7	Hygiene - U+A+D+L	26	Diet - A	45	Hyg. & vacc. (a) - D+L	64	Hyg. & diet - U+A
8	Hygiene - U+A	27	Diet - D	46	Hyg. & vacc. (a) - A+L	65	Baseline
9	Vaccine (a) - U	28	Diet - L	47	Hyg. & vacc. (a) - U+A+D+L	66	Hyg. & col. - U
10	Vaccine (a) - A	29	Diet - D+L	48	Hyg. & vacc. (a) - U+A	67	Hyg. & col. - A
11	Vaccine (a) - D	30	Diet - A+L	49	Hyg. & vacc. (b) - U	68	Hyg. & col. - D
12	Vaccine (a) - L	31	Diet - U+A+D+L	50	Hyg. & vacc. (b) - A	69	Hyg. & col. - L
13	Vaccine (a) - D+L	32	Diet - U+A	51	Hyg. & vacc. (b) - D	70	Hyg. & col. - D+L
14	Vaccine (a) - A+L	33	Colicin - U	52	Hyg. & vacc. (b) - L	71	Hyg. & col. - A+L
15	Vaccine (a) - U+A+D+L	34	Colicin - A	53	Hyg. & vacc. (b) - D+L	72	Hyg. & col. - U+A+D+L
16	Vaccine (a) - U+A	35	Colicin - D	54	Hyg. & vacc. (b) - A+L	73	Hyg. & col. - U+A
17	Vaccine (b) - U	36	Colicin - L	55	Hyg. & vacc. (b) - U+A+D+L		
18	Vaccine (b) - A	37	Colicin - D+L	56	Hyg. & vacc. (b) - U+A		
19	Vaccine (b) - D	38	Colicin - A+L	57	Hyg. & diet - U		

Chapter 5

Cost-effectiveness of controlling *Escherichia coli* O157:H7 in the Dutch beef-supply chain

Paper by Vosough Ahmadi B., Frankena K., Turner J., Velthuis A.G.J., Hogeveen H. and Huirne R.B.M., (2007). To be submitted.

SUMMARY

Dutch beef and beef products can be contaminated with VTEC O157. Interventions to reduce the contamination of beef with VTEC O157 can be applied at different levels of the beef-supply chain. To investigate the cost-effectiveness of interventions against VTEC O157 in the beef-supply chain, four available and constructed epidemiological and economic models were used. The costs-effectiveness of four on-farm interventions against VTEC O157, namely vaccination, colicin administration, diet modification and additional hygiene were determined and were compared with the cost-effectiveness of slaughterhouse decontamination methods. Results showed that for every 1% reduction in prevalence of VTEC O157-contaminated quarters, approximately €35,000 up to €541,000 per year is needed for applying decontamination methods to an industrial slaughter plant. The costs of implementing on-farm interventions for the supplying dairy farms to achieve the same goal was estimated to be €462,000 to >1 million per year. The results of this study indicate that applying interventions at slaughterhouse level is more cost-effective than implementing interventions at the farm level or at both levels.

1. INTRODUCTION

A recent human outbreak of *E. coli* O157:H7 (VTEC O157) due to the consumption of steak tartar (Doorduyn et al., 2006), as well as the results of the previous investigations (Heuvelink et al., 2001; Heuvelink et al., 1996; Heuvelink et al., 1999) confirm that Dutch beef and beef products can be contaminated with VTEC O157. Approximately 7% of the dairy herds are infected with VTEC O157 in the Netherlands (Schouten et al., 2004). Studies in the beef slaughterhouses showed that carcasses are contaminated with manure, but VTEC O157 was not isolated (Heuvelink et al., 2001). Interventions to reduce the contamination of beef with VTEC O157 can be applied at different levels of the beef-supply chain such as dairy herds, slaughterhouses, retailers or at consumer level. However, for a decision maker in the beef-supply chain, it is not known at which level implementing the interventions is the most cost-effective.

To provide such insight, the costs and effectiveness of the feasible interventions need to be investigated at each level of the chain. Moreover, the costs and effectiveness must be determined for the whole chain. The cost-effectiveness of some of the slaughterhouse decontamination methods to be applied in the Dutch industrial slaughterhouses was investigated (Vosough-Ahmadi et al., 2006; Vosough Ahmadi et al., 2006a). To complete a beef-supply chain perspective, in addition to the slaughterhouse level, studies are required to cover the dairy farms or the primary production level. The effectiveness of four on-farm interventions to reduce the prevalence of VTEC O157-infected lactating cattle has been studied (Vosough Ahmadi et al., 2007). However, there is no economic evaluation of possible on-farm interventions against VTEC O157. These are essential to perform a cost-effectiveness analysis. The cost-effectiveness of the on-farm interventions in terms of the ratio between the achieved reduction in prevalence and change in net costs to achieve this reduction is of great importance in ranking the selected interventions (Belli et al., 2001). This study includes the economics evaluation of on-farm interventions against VTEC O157 and the cost-effectiveness analysis of the interventions from a chain perspective.

The objectives of this paper are (i) to determine the costs of the four on-farm interventions, (ii) to explore cost-effectiveness analysis of the interventions against VTEC O157 at two levels of the Dutch beef-supply chain (i.e., farm and slaughterhouse) to identify the most promising intervention(s). The epidemiological and economic consequences of interventions in the beef-supply chain at each separate level and at the chain level were presented and analysed.

2. MATERIALS AND METHODS

In Figure 5.1 an overview of the modelling approach and the research design are presented. A slaughterhouse epidemiological model was available to evaluate the effectiveness of decontamination methods to reduce the prevalence of infected-carcass quarters (Vosough Ahmadi et al., 2006b). In addition, an economic model was available to calculate the implementation costs and the cost-effectiveness of the slaughterhouse interventions (Vosough Ahmadi et al., 2006a). Similarly, the effectiveness of four on-farm interventions, namely vaccination, diet modification, probiotics (i.e., colicin E7) and hygienic measures in reducing the prevalence of VTEC O157-infected dairy cattle were investigated using a farm epidemiological model (Vosough Ahmadi et al., 2007). In the following sections of the materials and methods, first an overview on the existing farm epidemiological model is presented, and then the constructed economic model and the costs aspects of the four on-farm interventions are described and finally the cost-effectiveness approach and sensitivity analysis are explained.

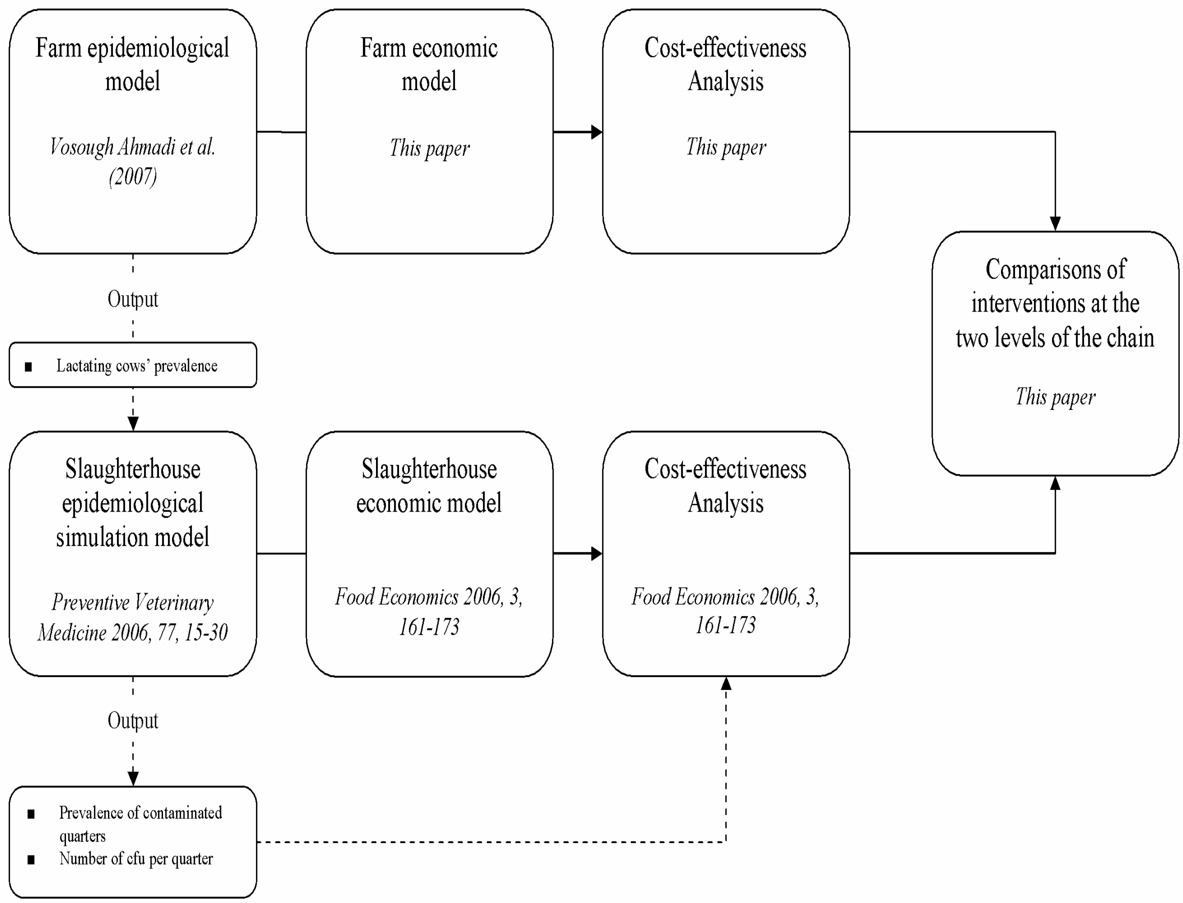

Figure 5.1. Schematic representation of the economic-epidemiological analysis of the interventions at the beef-supply chain.

2.1 Epidemiological model

The above mentioned transmission model to investigate the dynamics of VTEC O157 in a typical Dutch dairy herd, was used to assess the effectiveness of the on-farm interventions in reducing the prevalence of infected animals. The four management groups in the model were young stock under-six-months old (U), young stock above-six-months old (A), dry (D) and lactating (L) adult cattle. There were three categories of input variables in the model. The first category was related to the general dairy-farm management such as total herd size, maturation rate of the animals, and rate of flow from dry to lactating and vice versa. The second category consisted of the direct-transmission rates of VTEC O157 from animal to animal in the various groups. The third category included the group-specific and general indirect-transmission parameters, faecal-shedding rate, recovery rate and death rate of VTEC O157.

2.1.1 On-farm interventions

Intervention strategies against VTEC O157 can be categorized into antibacterial, probacterial, dietary interventions and management interventions (Callaway et al., 2004). One intervention from each of the categories mentioned, which were: vaccination, probiotics (i.e., colicin), diet modification and additional hygiene (i.e., more frequent cleaning bedding materials and water troughs) were selected based on literature.

Some parameters in the model, namely group-specific and general indirect-transmission parameters, faecal-shedding rate, recovery rate and death rate of VTEC O157 were deemed to be affected by the on-farm intervention measures. It was assumed that vaccination affects both faecal shedding and the recovery rate. However, diet modification and colicin affect only the shedding rate and additional hygiene only affects the pathogen death rate. The model was run using single interventions (i.e., using only one intervention in one or more animal groups) and combinations of hygiene with other interventions (i.e., hygiene was applied in all animal groups and other interventions were applied in one or more animal groups). Prevalence within the lactating-group and the herd prevalence were the model’s output of interest. The effectiveness of interventions was defined as the relative change of lactating-group prevalence and herd prevalence from the baseline. The model was run for 1,000 days for without- and with-intervention situations.

2.2 Farm economics model

An economic model was built based on the principles of partial budgeting, in which the economic consequences of a specific change in farm procedure are quantified (Dijkhuizen and Morris, 1997). The specific changes in terms of additional returns, reduced costs, returns forgone and additional costs were the positive or negative consequences of the on-farm interventions compared to the before intervention situation. The basic situations for different farm sizes were defined and then the partial budgets for every on-farm intervention were calculated. In the general format of a partial budgeting approach, the net costs are calculated as following:

Net Costs = (Returns forgone + Additional costs) – (Additional returns + Reduced Costs)

2.2.1 Dutch dairy sector

Some characteristics of the Dutch dairy farms, such as total herd size, available land for forage production and available labour affect the net costs of the implementation of the on-farm interventions. Therefore, to have a more realistic cost-estimation for the on-farm interventions, the mentioned characteristics of the dairy farms were taken into account According to the Dutch farm accountancy Data Network (LEI, 2004), three main categories of farm-size can be recognized in the country: farms with 57 (small), 100 (medium) and 223 (large) cattle in total. Close to 30% of the whole cattle farms have 57 cattle, 58% held 100 cattle and 12% have 223 cattle. The main characteristics of these farms that are relevant to our cost-calculation are summarized in Table 5.1. We assumed that with the same proportion, the mentioned farms in the three categories supply 500 culled dairy cattle to an industrial slaughterhouse in a daily basis. As such, 3,872 small farms, 3,653 medium farms and 389 large farms supply 289, 150, and 60 cattle per day.

2.2.2 Cost items of the selected interventions

Some technical peculiarities of the on-farm interventions that affect the implementation costs are explained next.

Diet modification. It has been shown that changing a conventional forage based diet to a grain based diet (i.e., more concentrates) reduces the number of colony forming units (CFU) of VTEC O157 excreted in faeces (Van Baale et al., 2004). We assumed for the baseline situation that the total daily feed intake was 20 kg of dry matter per day, for both summer and winter seasons. For <1 year-old young stock this is 5 kg of dry matter and for <1 year-old young stock and 6 kg for >1 year-old young stock. The diet of Dutch dairy cattle consists of fresh grass, grass silage, corn silage and concentrates, including grains, vitamins, minerals, etc. (Table 5.2). As an intervention in reducing the shedding rate, the concentrate content of the diet for an average milking cow, was increased from the baseline level (i.e., 25% in summer and 40% in winter) to 70% in both summer and winter. The change in diet for young stocks was gentler and incorporates an increase of the concentrate from 10% to 40% of the diet (Table 5.2).

Table 5.1. Characteristics of the dairy farms

Item	Characteristics of three farm categories (total number of cattle)			Unit
	57	100	223	
Number of dairy cow (D+L)	32	66	128	Cattle
Number of <1 calves	11	11	45	Calf
Number of >1 heifers	14	23	50	Heifer
Culling rate	0.039	0.079	0.154	Cow/farm/day
Proportion to all dairy farms	30	58	12	Percent
Fodder area	21	43	73	Hectare
Grass land	17	33	57	Hectare
Forage crop land (corn)	4	8	16	Hectare
Corn production	13,500	13,500	13,500	Kg DM/ha
Grass production	3,000	3,000	3,000	Kg DM/ha
Milk yield	7,320	7,600	7,770	Kg/cow/year
Number of cows by each category to supply 500 slaughtered animals per day	150	290	60	Culled dairy cow
Number of farms in each category supplying 500 animals to slaughterhouse	3,872	3,653	389	Farm

Additional hygiene. Transmission of VTEC O157 and other pathogens via the specific environment of each group of cattle on dairy farms was showed previously (Abdulmawjood et al., 2004; Cobbold and Desmarchelier, 2000; Hancock et al., 1998; Mechie et al., 1997; Rahn et al., 1997). Water troughs may become contaminated by the infected faeces or feed and bacteria survive and grow in the sediments for weeks or months (Hancock et al., 2001; Hancock et al., 1998; Wang and Doyle, 1998). Also, the bedding materials in the cubicles which are contaminated with manure are potential risk factors for the survival, growth and transmission of the bacteria (Kudva et al., 1998). Therefore, more frequently cleaning of the water troughs and an improved cleaning regime of the bedding environment were considered as on-farm interventions. It was assumed that in the baseline situation water troughs are cleaned once per month and cubicles are cleaned from the faeces on a daily basis and takes one minute per cattle. We assumed that in the new situation water troughs are being cleaned four times per months for 1.5 minutes per cattle (Table 5.3). As the cubicles are cleaned on a daily basis already, increasing the frequency is not practical. Thus, we assumed that only the length of the cleaning was increased to 1.5 minutes per cattle (Table 5.3). Furthermore, we assumed that the yearly required amount of straw and sawdust will be doubled by implementing additional hygiene for the bedding environment. With a better hygienic situation, the health status of the cattle might be enhanced and the losses due to many potential disorders might be prevented. However, because of the lack of precise data and to prevent complexity no additional returns or reduced costs to other pathogens were incorporated.

Table 5.2. Normal feed diet and modified diet of average dairy cows, calves < 1 year-old and heifers >1 year-old.

Item	Normal diet composition				Modified diet composition			
	Summer		Winter		Summer		Winter	
	% feed intake	Kg Dm/6 months	% feed intake	Kg Dm/6 months	% feed intake	Kg Dm/6 months	% feed intake	Kg Dm/6 months
Dairy cows		3,600		3,600		3,600		3,600
Fresh grass	35	1278	00	0	20	730	0	0
Grass silage	15	548	35	1278	5	183	20	730
Corn silage	25	913	25	913	5	183	10	365
Concentrate	25	913	40	1,460	70	2,555	70	2,555
Calves <1 age		900		900		900		900
Fresh grass	35	319	00	00	25	228	00	00
Grass silage	30	274	55	502	20	183	35	319
Corn silage	25	228	35	319	15	137	25	228
Concentrate	10	91	10	91	40	365	40	365
Heifers >1 age		1,080		1,080		1,080		1,080
Fresh grass	35	383	00	0	20	219	35	383
Grass silage	30	329	55	602	15	164	25	274
Corn silage	25	274	35	383	40	438	40	438
Concentrate	10	110	10	110	25	274	00	00

Vaccination. Recently, a newly developed vaccine was successfully tested in an experimental study to reduce the shedding rate of VTEC O157 (Potter et al., 2004). This vaccine raises antibodies that interfere with the gut colonization of the host (cattle or other hosts) by VTEC O157. As a result, a 10-fold reduction in log number of CFU bacteria per gram of faeces of cows was observed. Animals should be inoculated three times per year. The costs of the vaccination consist of the price of a single doze, inoculation costs per cattle and the costs related to the veterinarian visit (Table 5.3). No additional returns or reduced costs or return forgone could be identified for the vaccination against VTEC O157.

Colicin. Colicin is a product of colicinogenic *E. coli* that competes with VTEC O157 in the digestive tract of the animals and acts as a probiotic (Schamberger et al., 2004). It can be mixed with the other feed components at feed-producing companies or on-farm. We assumed that colicin was mixed into the feed at the feed company. Thus, the only costs are related to the increased product's purchasing price (Table 5.3). As there is no proven evidence of increase or decrease in milk yield or preventing other disorders due to the colicin administration, no additional return, reduced costs or returns forgone was considered for this intervention.

Table 5.3. Values and prices of input parameters to calculate the costs of on-farm interventions.

Item	Values and prices			Unit
	Minimum	Mode	Maximum	
Water trough cleaning (baseline)	-	1	-	Times/month
Consumed time for cleaning of water troughs (baseline)	-	1	-	Minutes/cow
Additional water trough cleaning (intervention)	2	4	8	Times/month
Additional consumed time for water trough cleaning (intervention)	1	1.5	2	Minutes/cow
Bedding cleaning/replacing (baseline)	-	30	-	Times/month
Consumed time for cleaning of bedding (baseline)	-	1	-	Minutes/cow
Additional consumed time for bedding cleaning (interventions)	1	1.5	2	Times/month
Straw and sawdust costs	15	18	25	€/cow/year
Vaccination frequency	1	3	6	Injection/cow/year
Vaccine price	1	2	4	€/dose
Vaccination costs by technician	108	270	810	€/year
Opportunity costs of labour	15	18	25	€/hour
Colicin price (mixed in feed)	0.01	0.02	0.04	€/cow/day
Grass silage production/purchase price	0.05	0.11	0.22	€/kg DM
Corn silage production/purchase price	0.06	0.12	0.24	€/kg DM
Concentrate purchase price	0.09	0.19	0.38	€/kg DM
Percentage of concentrate in adult cows' diet in summer and winter (as intervention)	40	70	90	%

2.3 Cost-effectiveness analysis

The costs of the interventions (ΔC) calculated in the economic models and the effectiveness, in terms of the reduction of prevalence (ΔP), estimated by the epidemiological simulation models and were used to calculate the cost-effectiveness (or effectiveness-cost) ratios. These ratios are used to rank the interventions and identify the most cost-effective interventions to reduce the prevalence (Belli et al., 2001):

$$EC = \Delta P / \Delta C_{year} \quad (1)$$

$$CE = \Delta C_{year} / \Delta P \quad (2)$$

To get a more comprehensive insight on the cost-effectiveness ratios, the least-cost frontier was drawn. This is done by graphing the costs per quarter against the effectiveness and connecting the points with the least cost and highest effectiveness. Farm, slaughterhouse and combination of these two levels were included for a comparison from the beef chain perspective.

2.3.1 Connecting farm and slaughterhouse models

The values of the input parameters, particularly animal-level prevalence and hide prevalence, of the slaughterhouse-simulation model (Vosough-Ahmadi et al., 2006) were updated. The new values were estimated by the farm epidemiological model (Vosough Ahmadi et al., 2007). Based on the outputs of the farm model, the animal-level prevalence (i.e., lactating group prevalence) and hide prevalence were estimated to be 5.02% and 10% respectively. As the farm epidemiological model was not able to estimate the change in between-herd prevalence (i.e., at region or country level), we did not change the default value (i.e., 7.2%) used in the slaughterhouse-simulation model. The slaughterhouse- simulation model was run with the new values (for both animal-level and hide-prevalence) as the result of on-farm interventions. Also, the model was run with the new input values as well as interventions at slaughterhouse considering a scenario that at both farm and slaughterhouse levels interventions are implemented. The output was the prevalence of contaminated beef carcass quarters at the end of the quartering stage at without intervention (baseline) and with-intervention situations (Figure 5.1).

Combinations of interventions at both farms on slaughterhouse can be applied. To consider some situations in which interventions are applied at both farms and slaughterhouse, we chose vaccination and hygiene from the farm level, and hide wash, irradiation and WS (hot-water wash plus steam-pasteurization) from the slaughterhouse level. High effectiveness was the main criterion of this selection, and the cost the next. The cost-effectiveness ratios for the combination sets were calculated.

2.4 Sensitivity analysis

To examine the robustness of the cost-calculations of the on-farm interventions as well as the outcome of the cost-effectiveness analysis from the chain perspective, sensitivity analyses were performed. The cost-generating items for the on-farm interventions such as extra labour time and purchased materials as well as the prices were included in the sensitivity analysis using their minimum and maximum values (Table 5.3). Also, the sensitivity of the cost-effectiveness ratios for the single interventions, at farm and slaughterhouse separately, in relation to minimum and maximum costs were examined. The effectiveness of each intervention was considered as a fixed value and minimum/maximum values were used for the costs.

3. RESULTS

3.1 Costs of on-farm interventions

Table 5.4 summarizes the results of the net costs calculations of the four interventions if applied to all animal groups. Modified diet was the most expensive intervention both at farm and cattle levels. It was more costly in the small size farms than medium and large ones due to economy of scale. It incurs €159, €150 and €136 per cattle per year in small, medium and large size farms respectively. Application of additional hygiene as an on-farm intervention was the second most costly intervention with slightly lower costs per cattle (€126 per cattle per year). Vaccination and colicin administration with costs of €9 and €7 per cattle per year were much less costly than the two mentioned interventions. Figure 5.2 illustrates the effectiveness of the four on-farm interventions, when applied to different groups of the animals on dairy farms, in reducing the lactating group prevalence, and their annual costs. Application of vaccination and colicin in different groups show higher reduction in baseline prevalence and less annual costs than hygiene and diet modification.

Table 5.4. Net costs of on-farm interventions per dairy farm size (applied to all animal groups) and per animal.

On-farm interventions	Net costs (€/year)					
	57		100		223	
	Farm	Cow	Farm	Cow	Farm	Cow
Modified feed	9,041	159	14,954	150	30,470	136
Additional hygiene	4,097	72	7,200	72	16,092	72
Vaccination	495	9	870	9	1,944	9
Probiotics (colicin)	415	7	730	7	1,632	7

3.2 Costs and effects of interventions at two chain levels

Table 5.5 represents the results of the cost-effectiveness analysis of 50 interventions at two levels of the beef chain (i.e., dairy farms and industrial beef slaughterhouse). The baseline prevalence of contaminated carcass quarters was estimated at 4.3%. The highest effectiveness (reducing the baseline prevalence by almost 100%) was achieved by irradiation and WLVHS at slaughterhouse. The highest effectiveness by on-farm intervention (reducing the prevalence of contaminated quarters by 95%) is due to vaccination of young stocks (i.e., U+A groups). Carcass trim was the cheapest intervention at slaughterhouse level (€0.22 per quarter) and irradiation the most expensive one (€4.65 per quarter). Interventions at the farm were far more costly than slaughterhouse level. Colicin applied to young stock (i.e., under six-month

Table 5.5. Cost-effectiveness ratio for interventions at two levels of the beef-supply chain.

Interventions at two chain levels - (Proportion (%) of the costs at each level)		Estimated quarter-level prevalence (%)	Estimated prevalence reduction (%)	Additional costs (€/quarter)	Cost-effectiveness ratio (ΔP/ ΔC), Effectiveness-costs ratio (ΔC/ ΔP) yearly costs for the chain per 1% prevalence reduction of contaminated carcass quarters and ranking		
Primary production	Slaughterhouse[1]	Mean	ΔP	ΔC	CE	Rank	EC
None (baseline scenario)	None (baseline scenario)	4.31	0.0	0.00	-	-	-
-	Carcass trim (T)	1.16	3.15	0.22	14.29	1	34,979
-	Carcass steam-pasteurization (S)	0.56	3.75	0.31	12.15	2	41,155
-	Carcass steam vacuum (V)	1.13	3.18	0.36	8.89	3	56,237
-	WT	0.81	3.50	0.44	7.91	4	63,180
-	Carcass lactic-acid rinse (L)	1.43	2.88	0.37	7.87	5	63,494
-	WS	0.15	4.16	0.53	7.84	6	63,755
-	WV	0.80	3.51	0.58	6.05	7	82,581
-	WTS	0.14	4.17	0.75	5.55	8	90,168
-	Carcass hot-water wash (W)	3.09	1.22	0.22	5.49	9	91,018
-	Hide wash with ethanol (H)	0.96	3.35	0.65	5.18	10	96,473
-	WVS	0.05	4.26	0.87	4.89	11	102,202
-	WLTS	0.05	4.26	1.12	3.82	12	130,952
-	WLVS	0.01	4.30	1.24	3.47	13	143,899
-	WLVHS	0.01	4.30	1.88	2.28	14	219,077
Vaccine in D – (75%)	WS – (25%)	0.15	4.16	2.14	1.94	15	257,211
Vaccine in D – (71%)	Hide wash with ethanol (H) – (29%)	0.96	3.35	2.26	1.48	16	337,506
Vaccine in U	-	2.50	1.81	1.67	1.08	17	462,057
Colicin in U	-	2.80	1.51	1.41	1.07	18	465,542
Colicin in U+A	-	0.39	3.92	3.65	1.07	19	465,584
Colicin in A	-	2.13	2.18	2.24	0.97	20	513,360
Vaccine in U+A	-	0.21	4.10	4.35	0.94	21	529,626
-	Carcass irradiation (Ir)	0.01	4.30	4.65	0.92	22	540,754
Vaccine in U+A – (95%)	Carcass hot-water wash (W) – (5%)	0.14	4.17	4.57	0.91	23	547,231
Vaccine in U+A – (89%)	WS – (11%)	0.03	4.28	4.88	0.88	24	569,335
Vaccine in A	-	2.00	2.32	2.67	0.87	25	577,245
Vaccine in U+A – (87%)	Hide wash with ethanol (H) – (13%)	0.18	4.13	4.99	0.83	26	604,268

Continue Table 5.5. Cost-effectiveness ratio for interventions at two levels of the beef-supply chain.

Interventions at two chain levels - (Proportion (%) of the costs at each level)		Estimated quarter-level prevalence (%)	Estimated prevalence reduction (%)	Additional costs (€/quarter)	Cost-effectiveness ratio (ΔP/ ΔC), Effectiveness-costs ratio (ΔC/ ΔP) yearly costs for the chain per 1% prevalence reduction of contaminated carcass quarters and ranking		
Primary production	Slaughterhouse[1]	Mean	ΔP	ΔC	CE_P	Rank	EC
Vaccine in D+A – (88%)	Carcass hot-water wash (W) – (12%)	2.84	1.47	1.83	0.80	27	622,950
Vaccine in D+A (26%)	Carcass irradiation (Ir) – (74%)	0.01	4.29	6.26	0.68	28	730,698
Colicin in L	-	1.83	2.48	4.82	0.52	29	970,614
Colicin in A+L	-	0.82	3.49	7.06	0.49	30	1,011,782
Vaccine in U+A – (48%)	Carcass irradiation (Ir) – (52%)	0.00	4.31	9.00	0.48	31	1,044,052
Colicin in D+L	-	1.69	2.62	6.18	0.42	32	1,177,819
Colicin in U+A+D+L	-	0.22	4.09	9.82	0.42	33	1,201,833
Vaccine in A+L	-	1.02	3.29	8.42	0.39	34	1,278,534
Vaccine in L	-	2.27	2.04	5.75	0.35	35	1,410,066
Vaccine in U+A+D+L	-	0.18	4.13	11.71	0.35	36	1,416,774
Vaccine in D+L	-	2.18	2.13	7.36	0.29	37	1,728,215
Colicin in D	-	4.14	0.17	1.35	0.12	38	4,038,990
Hygiene in U+A	-	0.79	3.52	35.98	0.10	39	5,115,291
Hygiene in U	-	2.99	1.32	13.86	0.10	40	5,252,683
Hygiene in A	-	2.24	2.07	22.12	0.09	41	5,355,445
Hygiene in D+L – (93%)	Carcass irradiation (Ir) – (7%)	0.01	4.29	65.56	0.07	42	7,636,953
Hygiene in D+L (99%)	WS (1%)	0.42	3.89	61.44	0.06	43	7,889,879
Diet modification in U	-	2.64	1.67	29.13	0.06	44	8,706,483
Hygiene in D+L – (99%)	Hide wash with ethanol (H) – (1%)	0.80	3.51	61.55	0.06	45	8,767,568
Diet modification in U+A		0.21	4.10	75.42	0.05	46	9,208,190
Diet modification in A	-	2.06	2.25	46.29	0.05	47	10,289,850
Hygiene (all) & vaccine. in U	-	0.30	4.01	98.56	0.04	48	12,277,147
Hygiene (all) & vaccine in U+A	-	0.19	4.12	101.23	0.04	49	12,299,811
Hygiene (all) & colicin. in U	-	0.23	4.08	100.53	0.04	50	12,317,629

1 Costs of the slaughterhouse interventions were quoted from Vosough Ahmadi et al. (2006b).

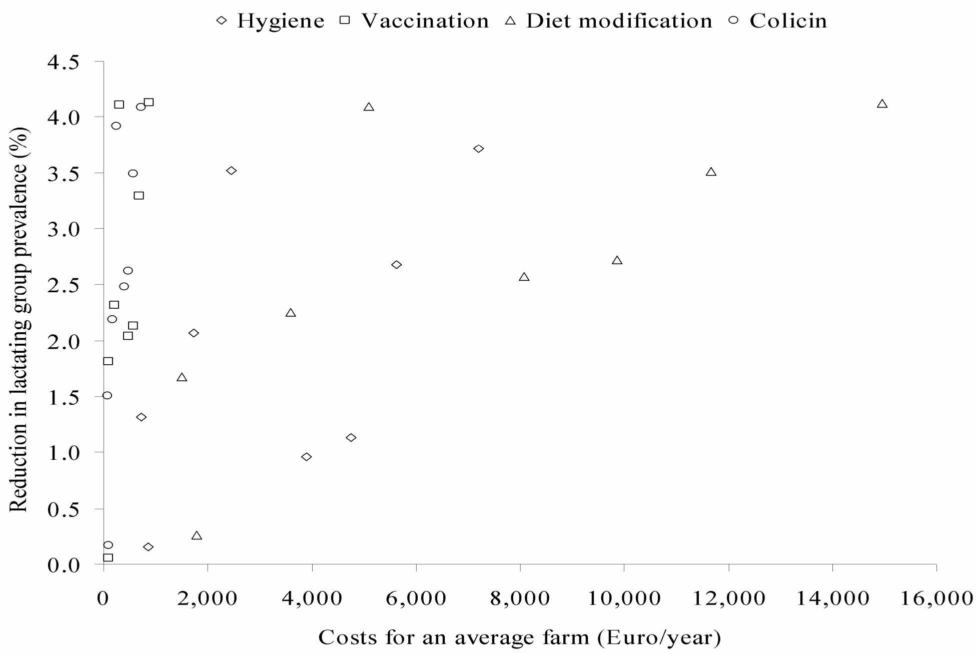

Figure 5.2. Costs and effectiveness of the four on-farm interventions. Interventions are applied to the different groups of animals on the farms namely: under six-month old (U), above six-month old (A), dry (D), lactating (L) and also following combinations: D+L, A+L, U+A and whole groups(U+A+D+L).

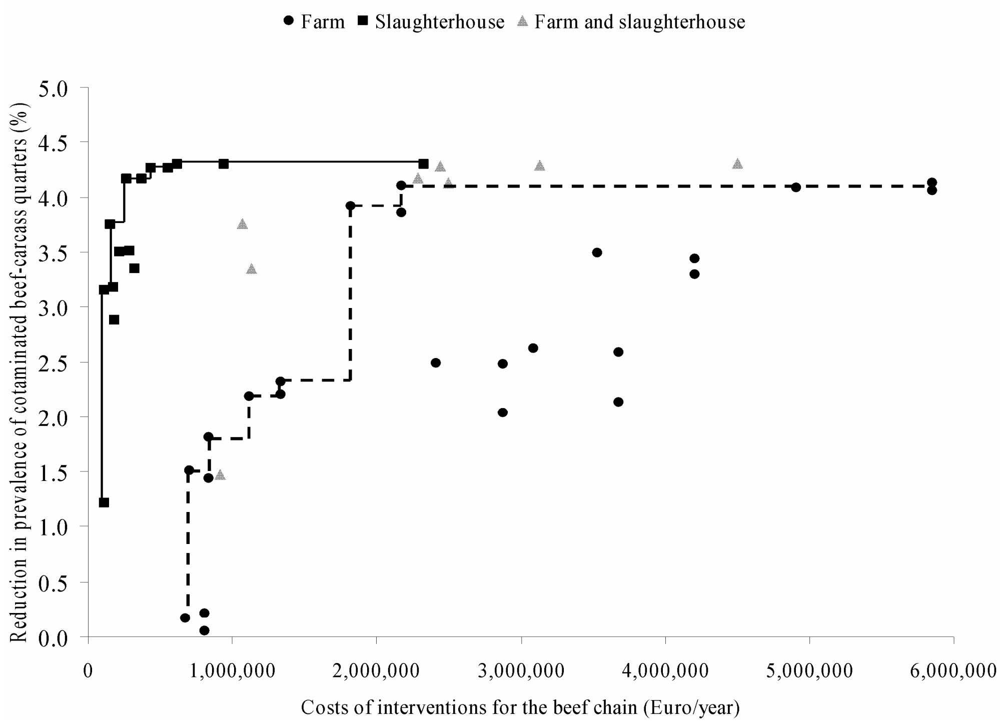

Figure 5.3. Least-cost frontier for interventions at two level of the beef chain: dairy farms and slaughterhouse. Continues line represents the least-cost frontiers of the slaughterhouse decontamination methods and dashed line represents the least-cost frontier of the on-farm interventions. Combinations of interventions at both levels are also resented as points.

group (U)), as the cheapest on-farm intervention costs €1.41 per quarter, and a combination of hygiene in all groups plus vaccination applied to young stock groups(i.e., U+A) costs €101 per quarter as the most expensive intervention.

All the interventions at the slaughterhouse level, except irradiation, showed a higher cost-effectiveness ratio than the interventions at the farm level (rank 1st to 14th of the Table 5.5). Rank 15th and 16th belong to implementing interventions at both the farms and the slaughterhouse. These interventions consist of a combination of vaccination in dry groups on farms and implementing WS (i.e., carcass hot-water wash plus steam-pasteurization) and/or hide wash (H) at the slaughterhouse. On-farm interventions and some other combinations at two chain levels are ranked from 17th to 50th.

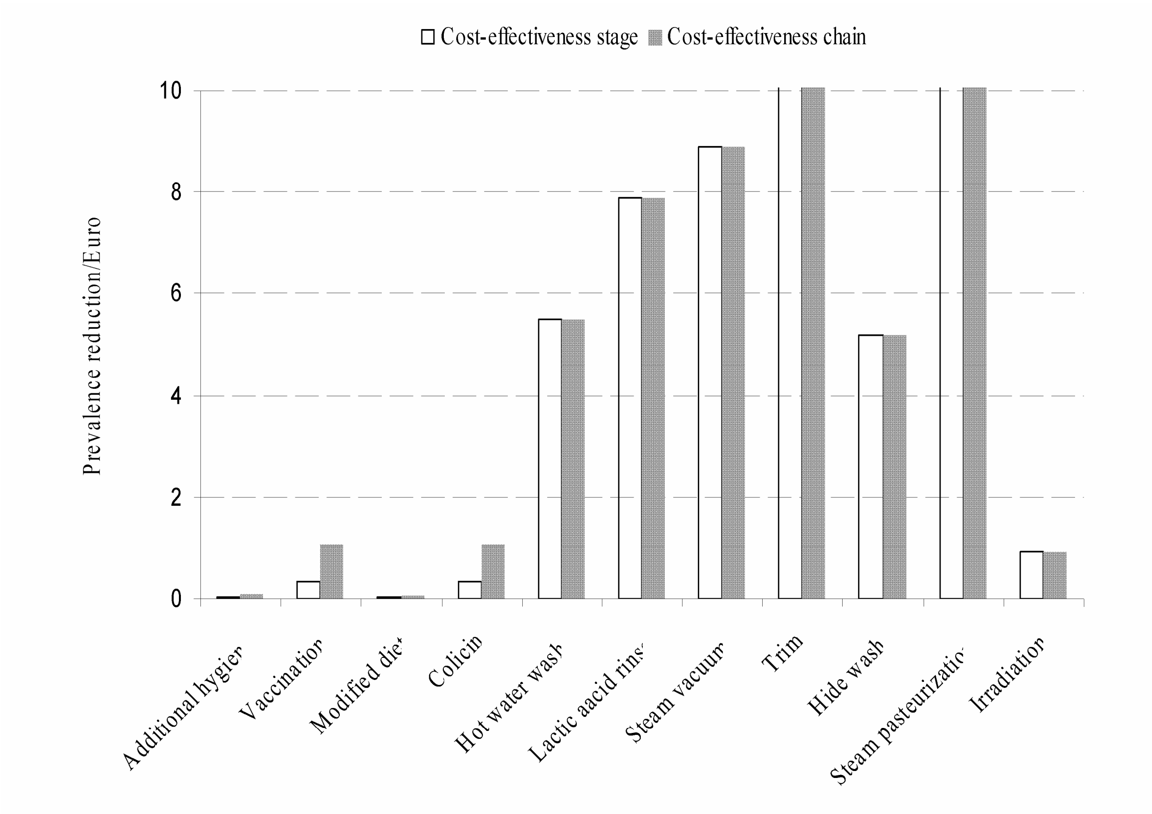

Figure 5.4. Comparison of the cost-effectiveness at two levels of the beef-supply chain. Given are the cost effectiveness from level (farm and slaughterhouse) and chain perspectives to reduce the prevalence of VTEC O157-contaminated quarters at slaughterhouse.

Figure 5.3 represents the costs and effectiveness of the interventions at two chain levels. The least-cost frontiers show that opposite to the on-farm interventions, slaughterhouse decontamination methods located mostly on the frontier. A comparison of the cost-effectiveness of the interventions from the stage and chain points of view is presented in Figure 5.4. At farm level, vaccination and colicin are more cost-effective at chain level than stage level. However, compared to decontamination measures at slaughterhouse, on-farm interventions are much less cost effective.

3.3 Sensitivity analysis

The sensitivity analysis of the effects of the cost-generating items on the net costs of the vaccination and colicin showed that the estimated costs for these interventions did not change. However, the estimated costs for the diet modification in an average farm size (i.e., 100 cattle) were sensitive to the concentrate price and its proportion in the feed (Figure 5.5).

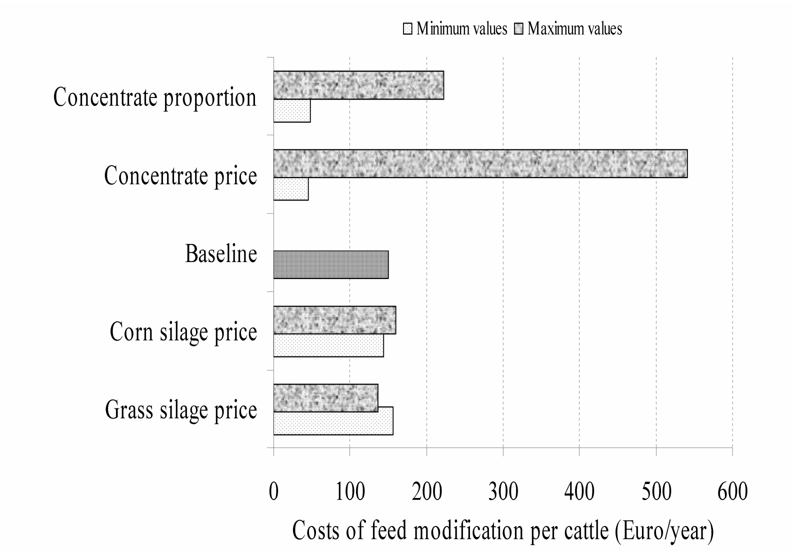

Figure 5.5. Sensitivity of diet modification cost-effectiveness ratio to the cost items.

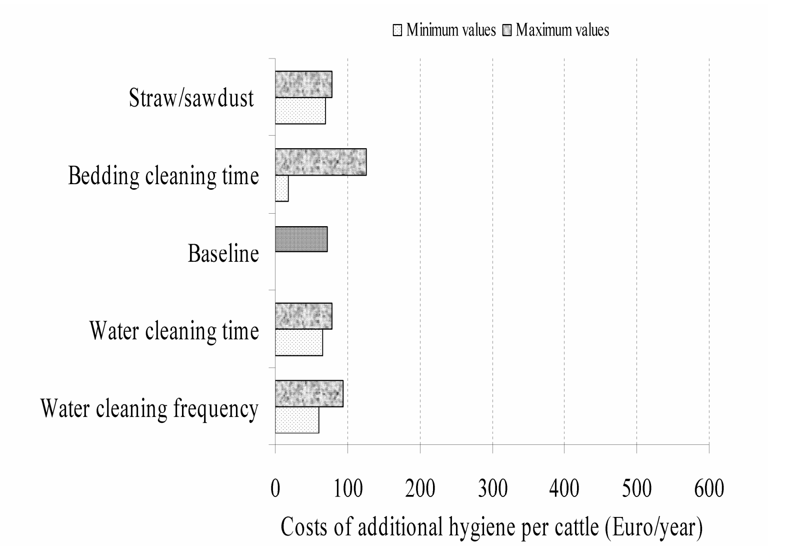

Figure 5.6. Sensitivity of additional hygiene cost-effectiveness ratio to the cost items.

Also, results showed that the costs of additional hygiene were sensitive to the length of the bedding cleaning (Figure 5.6). The frequency of water-trough cleaning affects the costs of the additional hygiene. Results of the sensitivity analysis of the on-farm interventions show that the cost-effectiveness ratios of vaccination and colicin are more sensitive to the costs than hygiene and modified diet (Figure 5.7).

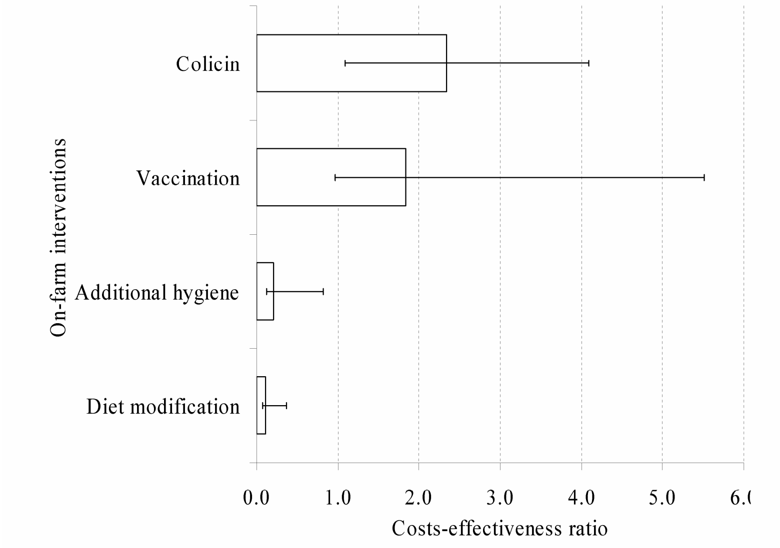

Figure 5.7. Comparison of the cost-effectiveness ratios of the four single on-farm interventions and the lower and upper bounds due to the lowest and highest costs.

4. DISCUSSION

The results of this study showed that targeting interventions at the slaughterhouse level of the Dutch beef chain is more cost-effective than implementing interventions at the farm level. To reduce the prevalence of contaminated quarters by 1%, interventions at the slaughterhouse level generate the annual costs of €35,000 to €219,000. However, at farm level the same goal is achieved as result of spending >€462,000 per year. The main reason for the higher costs at farm level is that interventions need to be applied at all the farms who supply the slaughter plant. In other words, to reduce the prevalence of infected animals on-farm (i.e., lactating group prevalence) interventions are implemented in around 7,000 farms. Compared to, slaughterhouse interventions are only applied at one firm. The same pattern was found by (Van der Gaag et al., 2004) on the interventions against *Salmonella* in the Dutch pork chain. Individual comparisons of one dairy farm and one slaughter plant show that the costs are much lower for a single farm than the costs for a slaughter plant. But as was, mentioned the costs from the chain perspective is higher than at farm level. An important assumption in this study is that all the dairy farmers in this chain are complying with the selected on-farm interventions. In practice, this is not realistic unless a strong controlling or reward/penalty system will exist. So, the effectiveness of on-farm interventions was overestimated.

Another issue is that by implementing the on-farm interventions in all the supplying farms, not only the animal prevalence will be affected but also the between farm prevalence is expected to decrease. This was not taken into account in our model. Therefore, the results of the effectiveness of on-farm interventions might be under-estimated.

Vaccination needs to be carried out three times per year to generate effective immunity (Potter et al., 2004). This frequency of vaccine administration might not be acceptable from an animal welfare point of view. Colicin administration is not time and energy consuming for the farmers, once it is mixed into the feed by the feed-producing company. Feed costs are one of the major elements in the net profit of the dairy farms. Thus, any diet modification might have a large impact on the farm economy. The diet modification in this study, changes the diet from forage as the basis to concentrate as the basis. This generates large costs. The increase of the concentrate from 40% of the diet to 70% might also increase the milk yield that was included in the partial budgeting. However, the increase in the milk yield is not sufficient to compensate the costs of the additional purchased concentrate. Moreover, a high level of concentration in the feed rations might increase the risk of metabolic diseases. These and other possible effects were not included in our calculations. So, the costs of a change in feed ration might be under-estimated. Additional hygiene was also very costly and because of the relatively low effectiveness was not between the high rank interventions at farm level. The main cost element of additional hygiene was labour costs that was assumed will be hired. However, in practice in majority of the cases costs of hired labour are not affordable.

5. CONCLUSIONS

We showed that, from the beef-supply chain perspective, applying interventions at slaughterhouse level is more cost-effective than implementing interventions at the farm level or at both levels. For every 1% reduction in prevalence of VTEC O157-contaminated quarters, approximately €35,000 up to €541,000 annually is needed for applying decontamination methods to an industrial slaughter plant. The costs of implementing on-farm interventions for the supplying dairy farms to achieve the same goal was estimated to be €462,000 to >1 million per year. We also showed that, form the farm perspective, the highest cost-effectiveness of the on-farm interventions in reducing the prevalence of VTEC O157-contaminated quarters at slaughterhouse are achieved by vaccination and colicin administration to the young stock groups.

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Chapter 6

General Discussion

1. INTRODUCTION

The overall objective of this research was to provide quantitative insight into the effectiveness and costs incurred by interventions in controlling *Escherichia coli* O157:H7 in the beef-supply chain. This objective was subdivided into two levels of the Dutch beef-supply chain: interventions on dairy farms and interventions at beef industrial slaughterhouses. The selected interventions at each level were examined to determine the best level to intervene and to identify the most cost-effective interventions. We used an epidemiological-economic framework, consisting of two epidemiological models for farm and slaughterhouse and two economic models. This last chapter is dedicated to elaborate on results described in chapters 2-5 and on different issues related to the control of VTEC O157 in the beef-supply chain. In section 6.2, the Dutch beef-supply chain is explained and the routes of introducing VTEC O157 to the supply chain are discussed. The pros and cons of our approach are discussed in section 6.3 and some future research areas are introduced. Section 6.4 deals with the possible public health impact of implementing the studied interventions. Implications of the results of this research for VTEC O157 policy, at country and EU levels are discussed in section 6.5 and a discussion on the ethics of food-safety is presented in section 6.6. Finally, the main conclusions of this thesis are given in section 6.7.

2. BEEF-SUPPLY CHAIN

Figure 6.1 illustrates an overview of the Dutch beef-supply chain. In the Netherlands beef is mainly produced from culled dairy cattle and can be considered as the by-product of milk production. Therefore, dairy farms are considered as the primary production site. Approximately, 23,500 dairy farms and seven industrial slaughterhouses are operating in the country. Domestic culled cattle along with some imported cattle are sent to the beef slaughterhouses. Approximately 14,500 and 2,430 live dairy cows are annually imported for slaughter and breeding purposes respectively, and a proportion of the cattle population (65,000 heads including breeding cattle) is exported. Close to 35.5% of the whole dairy cattle population, which is 1.433 million, are culled and slaughtered at domestic slaughterhouses annually (509,000 head or 158,000 tons) (PVE, 2006).

The beef consumption per capita per yer is calculated at 17.7 kg (PVE, 2005) which is equal to 290,600 ton for the whole nation. A large amount of the slaughtered animals are consumed by the Dutch consumers and the rest by consumers in other nations, mainly Italy, Germany, France and Russia.

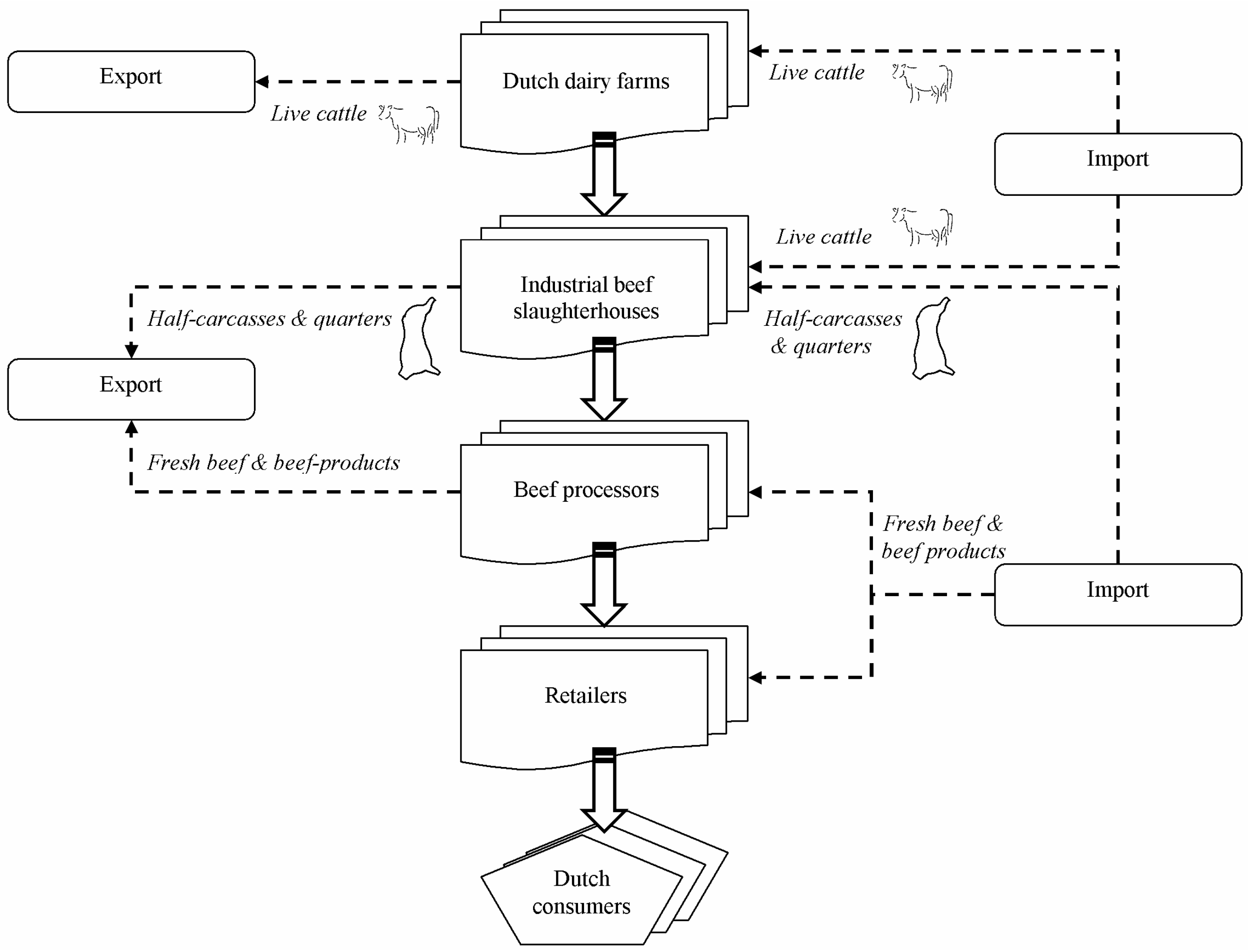

Figure 6.1. Schematic overview of the Dutch beef-supply chain.

VTEC O157 is present at 7.02% of the Dutch dairy farms (Schouten et al., 2004). Introducing the pathogen to the VTEC O157-free farms can happen via imported live animals, although this is not a large threat. Only 2,430 live cattle were imported in 2005 and about 60% of the farms are closed-farms. A large proportion (86%) of the annual imported live cattle is directly sent to the slaughterhouses. Depending on the country of origin, these animals can be infected or contaminated with VTEC O157 and they might pose a risk of beef contamination into the Dutch slaughterhouses. However, VTEC O157 prevalence in live cattle exporting countries such as Germany, Belgium and Poland are low (Beutin, 1999; Tutenel et al., 2002). This aspect was not included in our research. There is a large inflow of imported beef to the country in form of half-carcasses (73,000 tons), quarter of carcasses (8,300 tons) or processed beef and beef products (174,000 tons). A large proportion of the imported beef originates from Germany, Poland, Ireland and Brazil. The half-carcasses are imported as frozen and therefore there is a very low probability of introducing the bacteria via this route. But still imported beef includes some fresh and processed beef that can be potentially contaminated with VTEC O157 and it can play a role in any beef-related outbreak. Therefore, a preventive/controlling measure (e.g., test and sample) at this point might be considered. This issue was not dealt with in the current study and cost-effectiveness assessment of such a measure with respect to the probability of introducing the VTEC O157 via this route can be investigated in future research.

Another important issue regarding the beef-supply chain in the Netherlands is that a large amount of beef is exported but the data are lacking whether these are from domestic dairy cattle or not. The translation of this issue into the context of this research is that a noticeable part of the benefits of any VTEC O157 preventive/controlling interventions to increase the food safety of the Dutch beef is received by the consumers of the other nations (mainly Italy, Germany and France). Obviously, this might have a positive effect on enhancing the reputation of the Dutch beef industry that needs to be taken into consideration as an indirect benefit of interventions against VTEC O157. This issue was not covered in the current thesis. In fact in this study we did not cover the whole supply chain and our focus was on the dairy farms and slaughterhouses. Therefore, it is not possible to judge about the possible interventions at other levels of the beef-supply chain. It has been shown that interventions at the retailer level (e.g., more hygienic practice or lowering cross contaminations) or at consumer level (e.g., proper cooking) can be effective in some extent with low relatively low costs. However, the cost-effectiveness of interventions in the other levels of the beef-supply chain needs to be investigated in future studies. Similarly, the impact of the interventions on improving the public health was not covered in this research. But a brief overview on possible public health impact of interventions at the two levels of the beef-supply chain is given in section 6.4.

The research showed that the slaughterhouse is the most cost-effective level in the beef-supply chain at which a reduction in VTEC O157-infected beef can be achieved. However, it does not seem logical that the slaughter owners should bear the entire costs of the interventions that are estimated to be 16% to 40% of their profit per carcass (chapter 3 of this thesis). Therefore, some methods of sharing the generated costs should be invented and agreed upon in the entire industry and the beef-supply chain. The ethical aspect of this issue is discussed in section 6.6.

3. RESEARCH AND METHODOLOGICAL ISSUES

3.1 Modelling approach

In general two research approaches are available to conduct a research on epidemiology and economic consequences of interventions against food-borne pathogens (such as VTEC O157) in a food supply chain (such as beef chain): a positive approach and a normative approach.

The positive approach can be defined as a description of a relevant processes and characteristics by statistical/epidemiological data analysis (the so-called empirical modelling) (Dijkhuizen and Morris, 1997). In this approach, field studies are performed by putting the interventions in practice and by collecting field data. In many cases because the results are based on real-life data, the drawn conclusions and the followed policies are reliable. However, in most cases this approach is subject to some important constraints that make it difficult. As an example, implementing interventions on dairy farms to evaluate the effects, requires full cooperation of farmers and slaughterhouses and imposes them large costs. Evaluating interventions in experimental farms and experimental slaughter houses will also be very costly.

The normative approach includes computer simulation techniques that are methods for analysing a problem by creating a simplified mathematical model of the system under consideration which can then be manipulated by modification of inputs. This approach (the so-called mechanistic modelling) is especially attractive where real-life experimentation would be impossible, costly or disruptive and for exploring strategies that have not been applied yet (Dijkhuizen and Morris, 1997). In this approach, the real systems are mimicked in a virtual environment, based on available data and on assumptions. The best available estimates, as much evidence based as possible are used. Computer modelling can be based on analytical models or simulation models. Simulation models are used when the process to be modelled is too complex. In this study because of complexity of the dynamic of VTEC O157 on farms and in slaughterhouses simulation models were used. The results of our economic and epidemiological models were merged to perform a cost-effectiveness analysis. By using the epidemiological models we were able to evaluate the effectiveness of interventions while they were put in different levels of the supply chain (e.g., interventions at different groups of the farms or using decontamination methods at different stages of slaughter process). The developed models were verified by running the models using a variety of settings of inputs to make sure the outcomes matches with available knowledge and expectations in the related context. But, validation of the models, in particular the epidemiological models, was more complex mainly because data on VTEC O157 are scarce. Validation of the economics models was easier as they can be compared to the output of previous studies based on the real-life data in the same field or closed files (e.g., interventions against *salmonella* or other pathogens). The results of our cost calculations for the slaughterhouse interventions were close to a similar study in the Unites States (Jensen et al., 1998). Also, slaughterhouse and farm interventions were not that different compared with the costs of interventions against *salmonella* in the Dutch pork supply chain (Van der Gaag et al., 2004).

3.2 Modelling prevalence versus CFU

A literature review in the field of modelling food-borne pathogens reveals that there are two approaches used: modelling the proportion or prevalence of contaminated products and modelling the number of bacteria on the contaminated food units. Modelling the prevalence is mainly applied by scientists in the field of veterinary medicine. One reason might be that in that field, the health and disease status of animals are more important than the number of bacteria involved. The other reason is that the excretion rate is very variable and hard to measure. Moreover, the prevalence modelling is easier and quicker to develop and requires less data. However, when a highly infective pathogen such as VTEC O157 is the matter of interest, even the presence of a single bacterium might endanger public health. Thus, the second approach often used by the public health scientists and authorities, deals with modelling the exact load of the bacterial population on or in the end product. The advantage of prevalence modelling is that the available data can be used without making a series of assumptions that add to the complexity of the model. However, in CFU modelling, more assumptions are needed, mainly because of lack of relevant data.

In this study, we used prevalence modelling, both at the farm level and the slaughterhouse level. However, as we were dealing with highly infective VTEC O157 and the interventions at slaughterhouses reduces the bacterial population and eventually the prevalence, we modelled the effectiveness of interventions based on a CFU approach and we used this in our prevalence simulation model (chapter 2 of this thesis).

3.3 Types of economic analysis

Cost-effectiveness analysis is one form of economic analysis where the costs and consequences of interventions or programs are examined (Drummond, 1997). In other words the costs of an intervention are compared to the positive effects of that intervention. Thus, interventions are compared based two criteria: costs and effectiveness. If the costs are the only comparison criterion, then a cost-minimising analysis can be carried out. This can only be done when the effectiveness are the same. However, if the evidences of effectiveness are different and need to be estimated at the same time as the costs, then costs-effectiveness analysis is the best approach. The results of cost-effectiveness analysis are often expressed as a cost per unit of effect. We used cost-effectiveness analysis to rank and compare the interventions against VTEC O157 in the beef-supply chain, because we were not only interested in minimizing the costs of the interventions, but we also aimed to achieve a lower level of the contaminated beef. The second reason was that, given the complexity of the beef-supply chain and limited time and manpower we could not be able to cover the whole chain (up to consumers) and therefore a complete social cost-benefit analysis could not be performed.

4. IMPACT OF INTERVENTIONS ON PUBLIC HEALTH

In this study, the benefits of implementing interventions along the beef chain were estimated based on the reduction of prevalence of the infected beef carcass quarters at the end of slaughter process. However, in addition to this, the benefits of implementing the interventions are eventually received by the consumers and society as whole by reducing the number of VTEC O157-infected cases. Therefore, when evaluating the effectiveness of potential interventions in the beef-supply chain one of the main outcomes to be evaluated is the impact of VTEC O157 infections on human health status that can be expressed either in monetary measures or in health indices. It has been shown that, the cost-utility analysis approach can be applied to evaluate the economic and health impacts of interventions in controlling pathogens in supply chains (e.g., *campylobacter* in the chicken-supply chain) (Mangen et al., 2006). As the effectiveness in cost-utility approach is measured by any improvement in the health situation (i.e., quality adjusted life year (QALYs) or disability adjusted life year (DALY)), it was not feasible to apply in our study. Although, based on the mentioned points, cost-effectiveness analysis did not cover all the existed costs and effectiveness consequences of the interventions, but it successfully served us to compare and rank the interventions based on two criteria.

5. IMPLICATIONS OF THE RESULTS

5.1 Implications for the beef chain

The results show that the frequency of the contaminated beef units can be reduced by implementing interventions at two levels of the beef-supply chain. If the most effective on-farm interventions (to reduce the prevalence of infected lactating animals) are applied, a high reduction (>4%) in prevalence of contaminated beef can only be achieved if all the farmers comply to implement the interventions. In lack of any direct benefit or market incentives for the farmers, this condition might not be fully satisfied in practice. However, according to the results, the incurred annual costs for the most effective interventions (i.e., vaccination and colicin) for individual farms are low (€500 to €2,000 per farm per year which is 1% to 5% of their labour income). On the other hand the implementation costs of the interventions for the slaughterhouses were estimated to be 16% to 40% of their profit per carcass and therefore, in the lack of any compensation are not tempting. In such a situation, application of the studied decontamination methods in the Dutch industrial slaughterhouses highly depends on the frequency and size of proven beef-borne human outbreaks, national and EU food safety legislation as well as the risk attitude of the decision makers in the beef chain.

5.2 Implications for VTEC O157 policy

As it was mentioned in the previous chapters, dairy farms and culled-dairy cattle that are used for the beef production can be contaminated with VTEC O157 and the bacteria are detected from the retailers. Moreover, other enteric pathogens such different strains of *E. coli*, *salmonella* and *campylobacter* are also transmitted via contaminated beef. The results of this thesis showed that some decontamination methods at slaughterhouses can reduce the risk of the consumers in a cost-effective way. However, the characteristics and limitations of the models, as well the assumptions used in constructing the models and obtaining the mentioned outcomes should not be overlooked. Moreover, there are still questions and scepticism about the effectiveness of decontamination methods. This might prevent the food safety legislators at both national and EU levels to oblige the industry to implement those methods. Therefore, more experimental and field studies are required to minimize that uncertainty for a more protective policy.

The other issue is that implementing general interventions such as additional hygienic measures or diet modifications can be very effective but they are often also very costly without guaranteeing that they are fully applied in all the farms. It was showed that pathogen specific interventions are more effective than general interventions and impose far lower costs to individual farms. But they are still not as cost-effective as decontamination methods at slaughterhouses. Moreover, opposite to the pathogen specific interventions at farm level, carcass decontamination methods are not pathogen specific and reduced/destroys different pathogens. Despite of the good cost-effectiveness ratio of these methods, the negative consequences should not be overlooked. The adverse effects of the decontamination methods, such as bacterial resistance, recontamination and growth risk, and meat discolorations were not covered in this research and they need to be included in the future investigations.

6. ETHICAL REFLECTION OF THE FOOD SAFETY IMPROVEMENT

In recent years a series of crises due to food-borne pathogens such as *BSE*, *salmonella* and VTEC O157 have heightened public concerns in many countries about the safety of food (Dominguez et al., 2007; McCluskey et al., 2005; Schmid et al., 2007). Preventive and controlling measures can be taken along the food-supply chain to reduce the frequency of contaminated food and eventually to reduce the risk of human infections due to these hazards.

However, there is still no clear agreement between the three stakeholders of the food systems including: government (or state), the food industry and the public over the question "who should implement preventive/controlling measures". Besides an economic problem, this can be seen as an ethical dilemma. To have a good appraisal about the responsibility of food safety in a food system, this dilemma can be viewed and analyzed under different ethical approaches. Two ethical approaches namely: utilitarian and deontological approaches are used to analyze the mentioned dilemma and evaluate the positions of the government, the chain players in the beef industry and the consumers.

6.1 Utilitarian approach

Cost-benefit analysis is the process of weighing the total expected costs versus the total expected benefits of one or more actions in order to choose the best or most profitable option. In fact the roots of this approach can be found in the soil of the neoclassical economics. Neoclassical economics refers to a general approach to economics based on supply and demand which depends on individuals (or any economic agent) operating rationally, each seeking to maximize their individual utility or profit by making choices based on available information. In fact utilitarianism provides the philosophical basis for the cost-benefit analysis (Korthals, 2004). This approach focuses on the consequences of a certain action by trying to maximize the benefits, minimize the costs and in general, optimize the decision given the constraints. Under the utilitarian approach, the government wants to maximize the utility of the society as a whole as a general. In this way, government wants to increase the level of public health, reduce the prevalence of disorders and consequently the economical losses due to the diseases (Table 6.1). However, the ideal point that is to eliminate the risk and occurrences of the diseases cannot be reached mainly because of numerous diseases and limited public budget. Therefore the system of prioritizing of the diseases based upon a cost-benefit analysis is introduced (Kemmeren et al., 2006). In this system, public health problems imposing great economical losses to the society receive more attention (e.g. HIV aids) and less serious health problems (e.g. enteritis due to salmonellosis or VTEC O157) receive less attention.

Table 6.1. Analyses of food systems in relation to food safety from the view point of ethical approaches.

Approach	Government	Supply chain	Consumer
Utilitarianism	1- Issue regulations for industry to protect food safety (public health) 2- Interventions based on cost/benefit analysis	1- Cost-benefit analysis, no incentive to invest in interventions (major conflict between the chain players)	1- purchase food in a low price and high quality (willingness-to-pay)
Deontology	1- Obliged to protect food safety and invest in interventions (cost-benefit analysis isn't appropriate)	1- Obliged to protect food safety (maximum protection, cost-benefit analysis isn't appropriate)	1- Right to have access to safe food 2- Right to consume unsafe food

Every player in the industry (i.e. beef-supply chain in this thesis) tries to maximize his own profit. In the case of the beef-contamination with VTEC O157, the players who are located at the lower part of the chain (i.e., slaughterhouses or retailers) put the responsibility of any food-borne crisis on the shoulders of the primary producers (i.e. dairy farmers). However, as it was mentioned before, currently farmers do not have any incentives to implement extra measures. The main reason for this is that most of the enteric bacteria do not produce any symptoms or disorders in cattle and thus no economical losses are imposed to the farmers because of infections with this pathogen. Moreover, there is no market incentive for producing VTEC O157 free animals or VTEC O157 free meat. In the case of an outbreak that leads to a recall, the beef from the retailer stores; (using tracking and tracing systems) the main origin of the infections can be traced to the slaughterhouses up to the farms (except for ground beef). In recent years, an increasing number of product recalls and an increasing amount of claims being pushed back into the chain, have even emerged insurances against product recall in the food supply chains (Meuwissen, 2006).

Consumers, also maximize their own utility by purchasing the beef in a low price but with a high quality given their available budget. Thus, the willingness-to-pay of the consumers for VTEC O157-free beef can be measured.

The cost-effectiveness analysis carried out in this study can support decision making based on a utilitarian approach.

6.2 Deontological approach

The deontological approach is an ethical theory considered solely on duty and rights, where one has an unchanging moral obligation to follow a set of defined principles. Thus, the ends of any action never justify the means in this ethical system. If someone were to do their moral duty, then it would not matter if it had negative consequences (Table 6.1). From the deontological point of view, every person has a right of having access to sufficient food (food security) and safe food (food safety). These rights have been also recognized by the United Nations. Therefore, any food contamination with hazardous pathogens that ends up with a disorder (from mild symptoms up to death) is considered as violating the right of consumers to food safety. Thus, from the deontological point of view, the government must stimulate the industry to reach to a maximum protection against beef contamination. This can be done by issuing certain protective regulations that oblige every player of the supply chain (e.g., farmers, slaughterhouses, etc.) to have maximum protection level against the pathogens. Obviously, implementing interventions by each player of the chain in their business incurs costs and increases the production costs. This is an issue that a deontology person does not take into account, because he aims only to fulfil the food safety right of the consumers. However, scientific evidences show that having a zero probability of beef microbial contamination is almost impossible and as a result this right would never be fully met. Moreover, the food safety right has to be weighted against food security which has a higher priority than food safety.

6.3 Deliberative approach

Looking at the food safety issue from deontological point of view seems idealistic. Assigning the food safety right for every individual person in the society is a wonderful theoretical discourse. However, transferring this idea into the practical context looks like an ideal point that can never be achieved without scarifying some other rights or facts. Given the scientific fact that the zero contamination never can be reached, because of the essence of production and natural behaviour of the pathogen, we can expect that this right is always violating in the society. Nevertheless all the stakeholders in the food system (i.e. government, industry and consumers) can do their best to produce and consume the safest food possible. On the other hand all the food system stakeholders are currently acting in a utilitarian atmosphere that is based on neoclassical economics and market theory. Particularly this is a conflict in the industry itself. The chain players avoid increasing their costs and are therefore not interested to invest to improve food safety. In our opinion the government can play an important role by putting pressure on the players in the supply chain via issuing maximum protective regulations as well as frequent supervision over the production. In summary we can conclude that the responsibility of the food safety should be on the shoulders of the all stakeholders of the food system. Thus, a combination of the utilitarian and deontological ethical reasoning (or a deliberative approach) should be used in order to deal with this issue.

7. MAIN CONCLUSIONS OF THE THESIS

The research described in this thesis attempted to shed a light on epidemiogical and economic aspectes of different interventions in improving food safety in the beef-supply chain with respect to VTEC O157 contamination. The overall objective of this research was to provide quantitative insight into the effectiveness and costs incurred to the beef-supply chain due to the interventions in controlling VTEC O157. This objective was subdivided into two parts: interventions on dairy farms and interventions at beef industrial slaughterhouses. The following conclusions can be drawn from the results and the methodologies of this thesis:

- From the chain perspective, applying interventions at slaughterhouse level is more cost-effective than implementing interventions at the farm level or at both levels. For every 1% reduction in prevalence of VTEC O157-contaminated quarters, approximately €35,000 upto €541,000 per year is needed for applying decontamination methods to an industial slaughter plant. The costs of implementing on-farm interventions for the supplying dairy farms to achieve the same goal was estimated to be €462,000 to >1 milion per year.
- Carcass trim and steam-pasteurization are the most cost-effective decontamination measures that can be applied to a Dutch beef slaughterhouse in reducing the prevalence of VTEC O157-contaminated beef-carcass-quarters and CFU/cm^2 of the meat surface. However, using multiple decontamination measures generally would decrease quarter-level prevalence substantially more than most single decontamination meaures.
- Form the farm perspective, the highest cost-effectiveness of the on-farm interventions in reducing the prevalence of VTEC O157-contaminated quarters at slaughterhouse are achieved by vaccination and colicin administration to the young stock groups.
- From the farm perspective, vaccination, diet modification and colicin are more effective than implementing additional hygiene in reducing the lactating group prevalence. Moreover, treating young stock with these interventions is more effective than treating only adult cows.
- The costs of interventions for an individual dairy farm is much lower than the costs for a single industrial slaughter plant. The annual costs of the cheapest on-farm interventions were €730 to €870 per farm or €7 to €9 per cattle. The annual costs of the majority of the

decontamination methods at slaughterhouse were estimated to be €112,000 to €937,000 per slaughter plant or €0.9 to €7.5 per cattle.

- Modelling the prevalece of contaminated quarters is a useful approach in case of a low initial contamination (i.e. lower than 1.8 log CFU count). However risky events (such as gut rupture during the evisceration), which lead to a large number of bacteria on the carcasses, make modelling the number of CFU more suitable.

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Summary

Summary

Escherichia coli O157:H7 (VTEC O157) was first identified as a human food-borne pathogen in 1982 and since then it has been of concern to the public health authorities of countries such as USA, Canada, Japan, Scotland and UK, which have experienced several large outbreaks. A human infection with VTEC O157 is associated with a wide range of symptoms, including non-bloody diarrhoea, bloody diarrhoea, life-threatening complications such as hemolytic-uremic syndrome (HUS) particularly in children younger than five years, thrombotic thrombocytopenic purpura (TTP) in elderly people, and death. Based on epidemiological surveys in the Netherlands, it is estimated that the incidence of VTEC O157 originated diseases is 1,300 cases of gastroenteritis, 590 hemorrhagic colitis and 22 cases of HUS per year.

Cattle and the cattle farm environment are known as the most important reservoirs of this pathogen. Undercooked ground beef and steak tartar have been involved in many of the documented VTEC O157 outbreaks. So, the cattle sector plays an important role in the VTEC O157 food-borne risk. This pathogen can enter the beef-supply chain at multiple points and can cross-contaminate other products once present. It was shown that 1.1% minced-beef products were contaminated with VTEC O157 in the Netherlands. Furthermore, the result of a VTEC O157 risk-assessment study suggests that 0.3% of raw Dutch steak-tartar patties were contaminated with these bacteria. These observations, in addition to the first national food-borne VTEC O157-outbreak due to steak tartar consumption in 2005, confirm that Dutch beef and beef products can be contaminated with this pathogen.

Interventions that reduce the risk of beef-borne human outbreaks can be applied at pre-harvest level (i.e., on dairy-farm level) and/or post-harvest level (i.e., at slaughterhouse, retailer or consumer levels) of the beef-supply chain. However, it is not known at which level of the chain (i.e., farm or slaughterhouse) interventions are more cost-effective.

The overall objective of this research was to provide quantitative insight into the cost-effectiveness of interventions in controlling VTEC O157 at two levels of the Dutch beef-supply chain: dairy farms and industrial-beef slaughterhouses. The following research questions have been formulated:

- What are the most cost-effective interventions to be applied at Dutch dairy farms?
  - What is effectiveness of the on-farm interventions in reducing the prevalence of VTEC O157 infected lactating cows?
  - What are the costs of the on-farm interventions, per farm and per cattle?
- What are the most cost-effective beef-carcass decontamination methods to be applied in a Dutch industrial beef slaughter plant?

- What is the effectiveness of the selected decontamination methods, in terms of reducing the prevalence of contaminated beef carcasses quarters with bacteria and reducing the number of bacteria on the surface of contaminated beef carcasses quarters?
- What are the costs of applying decontamination methods per quarter of carcass, in an industrial slaughterhouse?
- What are the implications for the beef-supply chain? At which level of the chain interventions are the most cost-effective?

Figure S.1 illustrates the models and analysis that were explained and discussed in the thesis. A Monte Carlo simulation model was built to investigate the effectiveness of decontamination measures against VTEC O157 in a Dutch beef-industrial slaughterhouse in which 500 dairy cattle are slaughtered per day, (Chapter 2). Nine stages of the slaughter process were modelled. Within each modeled stage of the slaughter process the status of a carcass can change form negative (not-contaminated) to positive (contaminated) by two contamination routes. The status of a carcass can change from positive to negative by a decontamination route. The seven carcass-decontamination measures were: hot-water wash, lactic-acid rinse, trimming, steam-vacuum, steam-pasteurization, hide-wash with ethanol and gamma irradiation, and their combinations. There is a debate on modelling the number of bacteria on the surface of contaminated carcasses versus modelling the prevalence of contaminated carcasses. This issue was discussed (appendix, chapter 2) and the probability of eliminating the bacteria from the surface of the quarters by decontamination methods was estimated. The estimated daily prevalence of contaminated beef-carcass quarters by the simulation model was 9.2%, meaning that 9.2% of the carcass quarters had at least one CFU VTEC O157 on the surface. In chapter 5, the input data for the slaughterhouse simulation model were updated and the new estimation by the model was obtained. It was concluded that modelling the prevalence of contaminated quarters is a useful approach in case of a low initial contamination. However, risky events which lead to a large number of bacteria on the carcasses, make modelling the number of CFU more suitable.

The cost-effectiveness of seven decontamination measures to reduce VTEC O157-contaminated carcass quarters in a typical Dutch beef industrial slaughterhouse were explored (Chapter 3). To estimate the effectiveness, the stochastic epidemiological-simulation model (chapter 2) was used and to estimate the net cost a deterministic-economic model was developed. A reduction in the prevalence of VTEC O157-contaminated quarters to 2% using decontamination measures is achieved at costs of €0.20 to €0.50 per quarter, which is 16% to 40% of the net profit per carcass. A reduction to a prevalence of 1% will cost €0.50 to €1.00

per quarter. Additional carcass trim and carcass steam-pasteurization are considered as the most cost-effective decontamination measures with costs of € 6,340 and €20,243 per year to achieve a 1% prevalence reduction. Nevertheless, the lowest level of VTEC O157 prevalence, less than 1%, is achieved using a set of measures which costs between €1.00 to €2.00 per quarter or, by implementing irradiation which costs €4.65 per quarter.

A transmission model, developed to investigate the dynamics of VTEC O157 bacteria in a typical Dutch dairy herd, was used to assess the effectiveness of on-farm interventions in reducing the prevalence of infected animals in the lactating group (Chapter 4). The evaluated interventions were vaccination, diet modification, probiotics (colicin) and additional hygiene applied single or in combination. The estimated baseline prevalences of the lactating group and the herd prevalence were 5.02% and 13.96% respectively. Results showed that all four interventions, if applied to all animals or only to the young stock, are the most effective and will reduce the baseline prevalence by 84% to 99%. In general, combinations of hygiene and one of the other interventions have the highest effectiveness in reducing prevalence in the lactating group. Vaccination and diet modification showed a slightly higher effectiveness than colicin and hygiene.

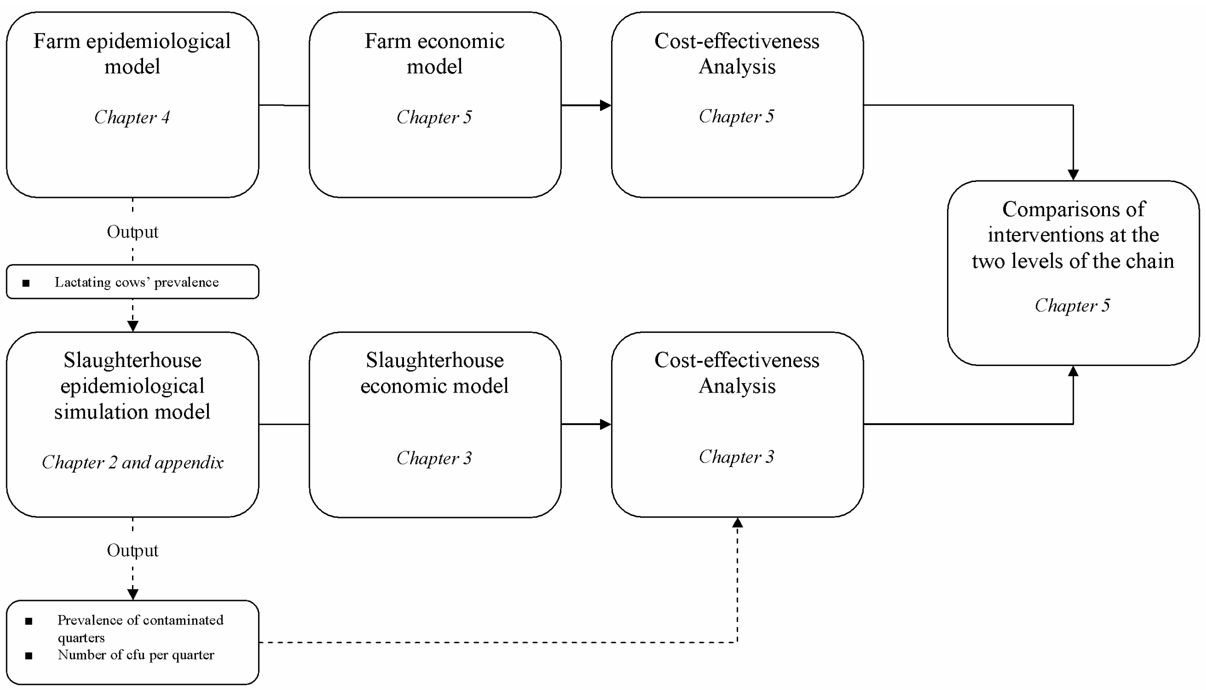

Figure S.1 Schematic representation of the models and analysis presented in the thesis

To investigate the cost effectiveness of interventions against VTEC O157 in the Dutch beef-supply chain, four within this research developed (epidemiological and economic) models were used (Chapter 5). The economic-deterministic model in which the yearly net costs of the on-farm interventions are calculated is described in chapter 5. The costs-effectiveness of the selected on-farm interventions to reduce the prevalence of VTEC O157 contaminated carcass quarters at slaughterhouse was determined and were compared with the cost-effectiveness of the slaughterhouse decontamination measures. The input for animal-level prevalence used in the slaughterhouse simulation model (Chapter 2) were updated based on the outputs of the farm epidemiological model that is presented in Chapter 4. The baseline prevalence of contaminated carcass quarters was estimated at 4.3% (Chapter 5). Results showed that for every 1% reduction in prevalence of VTEC O157-contaminated quarters, approximately €35,000 up to €541,000 per year is needed for applying decontamination methods to an industrial-slaughter plant. The annual costs of implementing on-farm interventions at the supplying dairy farms to achieve the same goal was estimated to be €462,000 to >1 million. The results of this study indicate that applying interventions at slaughterhouse level is more cost-effective than implementing interventions at the farm level or at both levels.

The overall results of this research show that the frequency of the contaminated beef quarters can be reduced by implementing interventions at two levels of the beef-supply chain. If the most effective on-farm interventions (to reduce the prevalence of infected lactating animals) are applied, a high reduction (>4%) in prevalence of contaminated beef can only be achieved if all farmers comply to implement the interventions. In lack of any direct benefit or market incentives for the farmers, this condition might not be fully satisfied in practice. However, according to the results, the incurred annual costs for the most effective interventions (i.e., vaccination and colicin) for individual farms are low (€500 to €2,000 per farm per year which is 1% to 5% of their labour income). On the other hand, two slaughterhouse decontamination measures namely, carcass trim and steam-pasteurization are the most cost-effective decontamination measures that can be applied to a Dutch beef slaughterhouse in reducing the prevalence of VTEC O157-contaminated beef-carcass-quarters. However, the implementation costs of the interventions for the slaughterhouses were estimated to be 16% to 40% of their profit per carcass and therefore, in the lack of any compensation are not tempting. In such a situation, application of the studied decontamination methods in the Dutch industrial slaughterhouses highly depends on the frequency and size of proven beef-borne human outbreaks, national and EU food safety legislation as well as the risk attitude of the decision makers in the beef chain.

Based on a discussion on the ethical dilemma about the responsibility of the food safety in the beef-supply chain (Chapter 6) and based on the cost-effectivenss analysis presented in this thesis, we believe that the responsibility of the food safety should be on the shoulders of all stakeholders of the food system (i.e., food-supply chain).

The objective of this research was to provide quantitative insight into the effectiveness and costs incurred to the beef-supply chain due to the interventions in controlling VTEC O157. The following conclusions can be drawn:

- From the chain perspective, applying interventions at slaughterhouse level is more cost-effective than implementing interventions at the farm level or at the chain.
- Carcass trim and steam-pasteurization are the most cost-effective decontamination measures that can be applied to a Dutch beef slaughterhouse in reducing the prevalence of VTEC O157-contaminated beef-carcass-quarters and CFU/cm^2 of the meat surface.
- From the farm perspective, the highest cost-effectiveness of on-farm interventions in reducing the prevalence of VTEC O157-contaminated quarters at slaughterhouse is achieved by vaccination and colicin supplementation to the young stock.
- The costs of interventions for an individual dairy farm are much lower than the costs for a single industrial slaughter plant.
- Modelling the prevalence of contaminated quarters is a useful approach in case of a low initial contamination. However, risky events which lead to a large number of bacteria on the carcasses, make modelling the number of CFU more suitable.

Samenvatting

Samenvatting

De bacterie *Escherichia coli* O157:H7 (VTEC O157) is voor het eerst onderkend als voedselpathogeen in 1982. Sindsdien is deze bacterie een zorg voor volksgezondheidsautoriteiten van diverse landen en vooral voor de USA, Canada, Japan, Schotland en Groot Brittanië, welke verschillende grote uitbraken hebben meegemaakt Een infectie met VTEC O157 kan gepaard gaan met symptomen variërend van (bloederige) diarree tot aan gevaarlijke complicaties zoals HUS bij kinderen en TTP bij ouderen, ziektes die een dodelijke afloop kunnen hebben. In Nederland is geschat dat er jaarlijks 1.300 personen ziek worden van VTEC O157, dat er 590 personen bloederige diarree ontwikkelen en dat 22 kinderen HUS krijgen als gevolg van deze infectie.

Een deel van de humane infecties zijn het gevolg van het eten van VTEC O157 besmet rundvlees of rundvleesproducten en daarom vormt de rundvleesketen een gevaar voor de volksgezondheid. VTEC O157 kan de rundvleesketen op verschillende plaatsen binnendringen en andere producten in de keten besmetten. Beheersmaatregelen in de keten kunnen het VTEC O157 risico terugdringen, maar de vraag is welke zijn het meest efficiënt?

Met dit onderzoek is kwantitatief inzicht verkregen in de kosteneffectiviteit van verschillende VTEC O157 beheersmaatregelen in de Nederlandse rundvleesketen; in het slachthuis en op melkveebedrijven. De volgende onderzoeksvragen zijn beantwoord:

- Wat zijn de meest kosteneffectieve VTEC O157 decontaminatie methoden in een groot Nederlands slachthuis?
  - Hoe effectief zijn de geselecteerde decontaminatie methoden in het reduceren van de prevalentie van VTEC O157 geïnfecteerde kwartkarkassen en in het reduceren van het aantal VTEC O157 bacteriën op de kwartkarkassen?
  - Wat zijn de jaarlijkse netto kosten van de decontaminatie methoden in een slachthuis?
- Wat zijn de meest kosteneffectieve VTEC O157 beheersmaatregelen op Nederlandse melkveebedrijven?
  - Hoeveel reduceren de geselecteerde VTEC O157 beheersmaatregelen de prevalentie van VTEC O157 geïnfecteerde melkkoeien?
  - Wat zijn de jaarlijkse netto kosten van deze beheersmaatregelen op melkveebedrijven?
- Wat zijn de meest kosteneffectieve VTEC O157 beheersmaatregelen in de Nederlandse rundvleesketen? Op welk niveau in de keten zijn maatregelen het meest kosteneffectief?

De effectiviteit van de decontaminatie methoden in een groot Nederlands slachthuis was geschat met behulp van een Monte Carlo simulatiemodel (Hoofdstuk 2). In dit model werden negen stappen van de slachtlijn gemodelleerd. Een (kwart of half) karkas kon in elke stap met VTEC O157 geïnfecteerd worden als gevolg van een riskante procedure of als gevolg van besmetting door de omgeving. Een geïnfecteerd karkas kon als gevolg van een decontaminatie methode weer de niet-geïnfecteerde status krijgen. Zeven decontaminatie methoden (en hun combinaties) zijn onderzocht: wassen met heet water, spoelen met melkzuur, extra trimmen, stoomvacuüm behandeling, stoom pasteurisatie, het wassen van de huid met ethanol en gamma bestraling. Uit deze studie blijkt dat een combinatie van decontaminatie methoden of gamma bestraling de meest effectieve decontaminatie methoden zijn in het slachthuis.

In de appendix van hoofdstuk 2 wordt een methode beschreven hoe een experimenteel gemeten reductie van het aantal bacteriën op een stuk rundvlees als gevolg van decontaminatie vertaalt kan worden naar de kans dat alle bacteriën van het karkas worden verwijderd. Ook wordt de discussie over het modelleren van de 'prevalentie' versus het modelleren van 'het aantal bacteriën op de karkassen' nader belicht. De conclusie is dat wanneer de initiële besmetting van een karkas laag is – zoals waarschijnlijk bij de meeste VTEC O157 contaminaties – het modelleren van de prevalentie geoorloofd is.

Een deterministisch economisch model waarmee de jaarlijkse netto kosten van slachthuis decontaminatie methoden worden berekend is beschreven in hoofdstuk 3. Tevens wordt in dit hoofdstuk de kosteneffectiviteit van de zeven decontaminatiemethoden berekend. Geconcludeerd is dat een reductie van de prevalentie van VTEC O157 gecontamineerde kwartkarkassen met 2% kan tegen kosten van €0.20 to €0.50 per kwartkarkas, wat 16% tot 40% van de netto winst per karkas is. Een reductie van de prevalentie met 1% kost €0.50 tot € 1.00 per kwartkarkas. Extra trimmen langs de slachtlijn en stoom pasteurisatie zijn de meest kosteneffectieve decontaminatiemethoden in het slachthuis en kosten €16,340 en €20,243 netto per jaar. Wanneer we als doel hebben dat de prevalentie met <1% afneemt zijn meerdere decontaminatie methodes nodig en zullen de netto kosten tussen de €1.00 en €2.00 per kwartkarkas liggen. Gamma bestraling is net zo effectief maar kost €4.65 per kwartkarkas.

Een transmissie model dat de dynamiek van VTEC O157 bacterien op een typisch Nederlands melkveebedrijf beschrijft is ontwikkeld om de effectiviteit van beheersmaatregelen op een melkveebedrijf te schatten (hoofdstuk 4). De effectiviteit hier is uitgedrukt in de reductie van de prevalentie van VTEC O157 geinfecteerde melkkoeien. De geëvalueerde beheersmaatregelen waren vaccinatie, een aangepast rantsoen, probiotica (colicine) en extra hygiene maatregelen. Combinaties zijn ook onderzocht. De geschatte prevalentie – zonder maatregelen – was 5,0% voor de melkkoeien en 14,0% voor alle dieren. Uit de resultaten blijkt dat alle vier interventies de prevalentie van VTEC O157 geinfecteerde melkkoeien reduceren met 84% tot 99%. Wanneer extra hygiene gecombineerd wordt met één van de andere interventies wordt de hoogste effectiviteit bereikt. Vaccinatie en een aangepast rantsoen hebben een iets hogere effectiviteit dan colicine en extra hygiene.

Hoofdstuk 5 beschrijft naast een deterministisch economisch model waarmee de jaarlijkse netto kosten van de boerderij interventies zijn berekend de evaluatie van de kosteneffectiviteit van alle geselecteerde beheersmaatregelen in de rundvleesketen. Hiervoor zijn de twee epidemiologische modellen (van boerderij en slachterij) gekoppeld en wordt de effectiviteit van maatregelen uitgedrukt in de reductie van de prevalentie van gecontamineerde kwartkarkassen aan het einde van de slachtlijn. De twee economische modellen zijn gebruikt voor het inschatten van de netto kosten. De geschatte VTEC O157 kwartkarkas prevalentie is 4,3%. De jaarlijkse netto kosten voor een slachthuis om met behulp van decontaminatie methoden de prevalentie met 1% te reduceren liggen tussen de €35.000 tot €541.000. Wanneer we hetzelfde doel willen bereiken met beheersmaatregelen op de melkveebedrijven die de dieren aan de slachterij leveren worden de jaarlijkse netto kosten geschat op €462.000 tot meer dan 1 miljoen Euro. Geconcludeerd kan worden dat maatregelen op het slachthuisniveau kosteneffectiever zijn dan maatrelgen op boerderijniveau.

In de algemene discussie van dit proefschrift worden een aantal aspecten nader belicht (hoofdstuk 6). Een reductie van meer dan 4% in VTEC O157 besmette kwartkarkassen met behulp van effectieve boerderij maatregelen (te weten vaccinatie en colicin) is alleen haalbaar wanneer alle veehouders de maatregelen ook 100% uitvoeren. Hoewel de jaarlijkse kosten van deze maatregelen voor de individuele bedrijven laag zijn (€500 tot €2.000 per bedrijf per jaar ofwel 1% tot 5% van hun inkomen) zal bij een gebrek aan een direct voordeel of stimulans de conditie van 100% uitvoering in de praktijk moeilijk haalbaar zijn.

Wanneer een slachthuis de één van de twee meest kosteneffectieve maatregelen (extra trimmen of stoom pasteurisatie) zal moeten toepassen, zal dit 16% tot 40% van hun huidige winstmarge kosten. En daarom is het implementeren van deze maatregelen niet erg aantrekkelijk voor de slachthuiseigenaren. De beslissing om één van de slachthuis decontaminatiemethoden te implementeren zal naast het financiele plaatje ook afhangen van de frequentie en groottes van VTEC O157 uitbraken en nationale en internationale voedselveiligheidsregelgeving, maar ook van de risicohouding van de beslissingnemers in de rundvleesketen.

In hoofdstuk 6 wordt ook een uiteenzetting over het ethische dilemma met betrekking tot de verantwoordelijkheid voor voedselveiligheid in de rundvleesketen gegeven. Op basis hiervan kan geconcludeerd worden dat iedere stakeholder in de rundvleesketen verantwoordelijkheid draagt voor voedselveiligheid.

Het doel van dit onderzoek was een kwantitatief inzicht krijgen in de kosteneffectiviteit van verschillende VTEC O157 beheersmaatregelen in de Nederlandse rundvleesketen; in het slachthuis en op melkveebedrijven. De volgende conclusies kunnen worden getrokken:

- Extra trimmen of stoom pasteurisatie zijn de meest kosteneffectieve VTEC O157 beheersmaatregelen in de rundvleesketen (en op slachterijniveau).
- Vaccineren van jongvee of het voeren van colicine aan jongvee zijn de meest kosteneffectieve VTEC O157 beheersmaatregelen op Nederlandse melkveebedrijven.
- VTEC O157 beheersmaatregelen op het slachthuisniveau zijn over het algemeen kosteneffectiever dan op boerderijniveau.
- De netto kosten om VTEC O157 te beheersen door middel van boerderijmaatregelen is voor een individuele melkveehouder veel lager dan de netto kosten die een individuele slachthuiseigenaar moet maken voor slachthuismaatregelen.
- Het modelleren van de prevalentie van besmette karkassen is een goede methodiek wanneer de initiële besmetting van een karkas laag is. Bij risicovolle gebeurtenissen die leiden tot een hoge initiële besmetting is het modelleren van het aantal bacteriën beter.

PUBLICATIONS

Refereed scientific papers

Vosough Ahmadi, B., Velthuis, A.G.J., Hogeveen, H., Huirne, R.B.M. (2006). Simulating *E. coli* O157:H7 transmission to assess effectiveness of slaughterhouse interventions. Preventive Veterinary Medicine, 77, 15-30.

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Conference papers

Vosough Ahmadi, B., Velthuis, A.G.J., Hogeveen, H., Huirne, R.B.M. (2003). Economics of *E. coli* O157:H7 risk reduction: a preliminary study. The Safe consortium, FOSARE seminar series. April 24-25 Brussels, Belgium.

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Curriculum Vitae

Bouda Vosough Ahmadi was born on February 15th, 1975 in Abadan, southwest of Iran. He accomplished his high school in biological sciences in 1992. He started his higher education studies at Azad University, faculty of veterinary medicine (Karaj branch, Tehran province) and received a DVM degree in the field of veterinary medicine in 1998. After two years working as a licensed veterinary practitioner in Tehran province, he started a master degree in the field of agricultural economics and management at Wageningen University in the Netherlands. He obtained his M.Sc. degree, specialized in animal health economics, in January 2003. The subject of his master thesis was epidemiology and economics of interventions against VTEC O157 in the beef chain and it became a basis for the proposal of his PhD project. From April 2003 to May 2007, he was working on his PhD project entitled "Cost-effectiveness of *Escherichia coli* O157:H7 control in the beef chain" at the Business Economics Group of Wageningen University. He followed his PhD education program in the Mansholt Graduate School of Wageningen University. He defends his PhD dissertation on May 25th, 2007 and will continue working as a researcher.

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Mansholt Graduate School of Social Sciences (MG3S)
Completed Training and Supervision Plan

Description	Institute / Department	Year	Credits*
Courses:			
Techniques for Writing and Presenting a Scientific Paper	Mansholt Graduate School of Social Sciences (MG3S)	2003	1
Mansholt Introduction Course	Mansholt Graduate School of Social Sciences (MG3S)	2003	1
Research Methodology: Designing and Conducting a PhD Research Project	Mansholt Graduate School of Social Sciences (MG3S)	2003	2
Scientific Writing	Language Centre of Wageningen University	2004	1.5
Food-Safety Risk Analysis	Mansholt Graduate School of Social Sciences (MG3S)	2003	3
Management of Microbiological Hazards in Foods	Food Sciences Graduate School (VLAG)	2004	1
Food Policy in an Era of Globalisation	Mansholt Graduate School of Social Sciences (MG3S)	2004	3
Multiple Criteria Analysis for Agricultural Decisions	Mansholt Graduate School of Social Sciences (MG3S)	2005	1.5
Ethical Dilemmas for Life Scientists	Wageningen Graduate Schools	2005	2
Animal Health Economics	Wageningen University	2003	3
Governance for Quality in Tropical Food Chains	Mansholt Graduate School of Social Sciences (MG3S)	2006	0.5
PhD Discussion Groups	Business Economics, Wageningen University	2003-2007	4
Assistant in Teaching Food-Safety Economics Course	Wageningen University	2006	0.7
Presentations at conferences and workshops:			3
SAFE Consortium Congress, Brussels, Belgium		2003	
ISVEE 10th Symposium, Vina del Mar, Chile		2003	
ICoMST 50th Congress, Helsinki, Finland		2006	
VEEC, Symposium, Lelystad, The Netherlands		2006	
SVEPM 18th Annual Seminar, Exeter, England		2006	
ISVEE 11th Symposium, Cairns , Australia		2006	
Multidisciplinary Seminar, MG3S PhD Day, Wageningen, The Netherlands		2006	
Total (minimum 20 Credits)			**27.2**

*One credit represents on average 40 hours of course work
SAFE Consortium: European Association for Food Safety
ISVEE: International Society for Veterinary Epidemiology and Economics
ICoMST: International Congress of Meat Science and Technology
VEEC: Dutch Association for Veterinary Epidemiology and Economy
SVEPM: Society for Veterinary Epidemiology and Preventive Medicine

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