Multi-criteria decision analysis (MCDA) for control of transboundary livestock diseases using the example of the 2010/11 foot-and-mouth disease (FMD) outbreak in the Republic of Korea

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I hereby certify that the thesis has not been submitted for a higher degree at any University or Institution and work embodied in this thesis is my work unless noted otherwise in the acknowledgements.

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Abstract

Decisions regarding transboundary livestock disease control strategies differ from personal decisions, such as buying groceries, in important ways: the stakes are high and the outcome of a decision will affect people in different fields. Decision making for transboundary livestock disease control strategies requires consideration of a number of factors including the epidemiology of the disease, economic cost of control, and environmental and social impact. For example, when applying pre-emptive slaughtering as a control measure for FMD, decision makers need to consider the epidemiologic effectiveness of the control measure, financial loss to farmers, the operational cost of slaughtering, negative impacts on the environment due to burning or burial of culled animals, and the public's concerns for the welfare of slaughtered animals. Therefore, it can be challenging for decision makers to choose the best control strategy among alternative strategies. The study presented in the thesis describes the application of multi-criteria decision analysis (MCDA) process as a decision support tool for decision making about transboundary livestock disease control strategies using an example of a simulated FMD outbreak.

The first research chapter (**Chapter 3**) investigates the preferences of chief veterinary officers (CVOs) for the criteria of FMD-control strategies in the Asia-Oceania region, which comprises countries free from or having experienced FMD. Criteria were grouped into epidemiologic, economic, and social-environmental. The CVOs in the Asia-Oceania region considered the epidemiologic criterion more important than the economic or the social-environmental criterion. The importance of the economic criterion differed with FMD status of a country: specifically, those countries considered free of FMD ranked the economic criterion as more important than those without. Among the criteria comprising the epidemiologic criterion, the most important was the size of the FMD-infected area, defined as the geographical size of FMD outbreak area. Within the economic criterion, the operational cost of the FMD-control strategy was considered the most important, and within the social-environmental criterion, the mental health of FMD-affected farmers was the most important criterion.

Chapter 4 describes the construction of an epidemiologic model of the spread of the 2010/11 FMD outbreak in the city of Andong, Republic of Korea, to measure the epidemiologic effectiveness of FMD-control strategies. According to the simulation results, the model accurately represented the FMD outbreak in two ways: 1) the median number of simulated FMD-detected farms was the same as the number of detected farms during the actual FMD epidemic, and 2) the simulated epidemic curve was similar to the actual epidemic curve for the 2010/11 FMD epidemic. Thus, the constructed model could be used as a reference for evaluating the effectiveness of alternative FMD-control strategies.

The control strategy applied during the 2010/11 FMD epidemic consisted of a pre-emptive slaughter area with a radius of three kilometres, 100 day movement restriction, and vaccination of all FMD-susceptible animals in the country. This was used as a baseline strategy in the study. Alternative levels of these control measures for the FMD-control strategy were simulated to evaluate the effect of alternative strategies. Changes in control measures were: 1) pre-emptive slaughtering within a radius of 0.5, one, and five kilometres of FMD-infected farms; 2) movement restriction of 30 days and 60 days; 3) ring vaccination in a band three to five kilometres from FMD-infected farms. According to the simulation results, the five kilometres slaughtering strategy resulted in the fewest FMD-infected farms.

Cost-effectiveness (CE) analysis was applied to evaluate the economic effectiveness of FMD-control strategies using the results of epidemiologic simulation model (**Chapter 5**). This showed that ring vaccination in a band three to five kilometres from FMD-infected farms was the most cost efficient among alternative FMD-control strategies. The other FMD-control strategies, in decreasing order of economic efficiency, were five kilometre slaughtering, 30 day stop movement, and 60 day stop movement. The 0.5 kilometre and one kilometre slaughtering strategy were excluded in the analysis because these strategies did not control FMD spread during the simulations.

Chapter 6 describes the MCDA process for choosing the optimal FMD-control strategy based on the results from **Chapters 3**, **4** and **5**. The measurements of the criteria were merged with the weight of criteria to calculate the overall score of each FMD-control strategy. In the Asia-Oceania region, CVOs preferred ring vaccination over alternative FMD-control strategies, with 30 day stop movement being the least preferred of the FMD-control strategies.

The findings presented in each of these chapters have broadened our knowledge of the decision making process regarding FMD-control strategies. The processes were reliable, transparent, and reproducible and can be applied not only to FMD but also to other transboundary livestock diseases such as classical swine fever or highly pathogenic avian influenza.

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Nomenclature

AUD	Australian Dollar
BCA	Benefit-Cost Analysis
BDI	Beck Depression Inventory
CSF	Classical Swine Fever
CVO	Chief Veterinary Officer
EU	European Union
FMD	Foot and Mouth Disease
FRF	French Franc
GBP	Great Britain Pound
HPAI	Highly Pathogenic Avian Influenza
KOSTAT	Statistics Korea
MCDA	Multi-Criteria Decision Analysis
MOSPA	Ministry of Security and Public Administration
OIE	The World Organization of Animal Health
USD	United States Dollar

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Chapter I

1 General Introduction

1.1 Introduction

Successful control of transboundary livestock diseases is based upon decisions about the suitability of control strategies. The decision making process needed to ensure a successful disease control outcome is often complex and must draw upon various considerations, such as the characteristics of disease, the costs of applying interventions, or the environmental effects of a control strategy. Additionally, the decision maker relies on the estimation of the disease impact and the forecast effectiveness of control measures. However, considering different sources of information at the same time is difficult. Important information might not be available and decisions might be made in an environment of uncertainty.

Decision makers can be aided by modelling, where a control method is selected considering all conflicting needs. The aim of modelling is to help the decision maker formulate the problem and establish a solution. The model starts by breaking complex problems, characterized by any mixture of objectives, into manageable pieces and scoring each piece in order to assess possible alternatives. Then, the analysis reassembles the pieces to present a coherent overall picture to decision makers. A criterion for each piece is set to evaluate the alternatives in a quantitative way. For example, Mourtis et al. (2011) evaluated the effectiveness of a classical swine fever (CSF) control strategy with three criteria, categorised as epidemiologic, economic, and ethical. The CSF-control strategy was scored for each criterion and the sum of all scores calculated to estimate the overall score. To account for differing preferences between stakeholders, multiple criteria can be created. It is beneficial for decision makers to use a multiple criteria model since it can emphasize different stakeholders' preferences. Multiple criteria models can allow estimates of the relative importance of objectives and criteria to stakeholders. Therefore, this type of modelling can provide decision makers with a systematic methodology to combine inputs from various stakeholders and to rank alternatives.

Until recently, the application of decision making models in selecting control strategies for transboundary livestock diseases such as foot and mouth disease (FMD) has been limited due to the complexity of its methodologies. Decision making in the animal disease context is a complex process, requiring the characterisation of epidemiologic, economic, environmental, and social values. Epidemiologic criteria include the duration of disease epidemics, the outbreak area size, or the number of disease infected animals. Economic criteria include the cost of the control strategy, financial losses for disease impacted farms, or loss in the livestock industry. In addition, animal health management and animal welfare are also important in decision making. The attitude of decision makers towards these criteria will affect the decision making process by influencing perceptions and benefits associated with the decisions. At a national level, policies for controlling transboundary livestock diseases must consider the varying perspectives of different stakeholders, such as interests of the farming community, the processing industries, the consumers or the public. These views often conflict with each other; for example, economic benefits for farming communities must be weighed against the interests of the public, or animal welfare issues must be weighed against the views of the farming community. Therefore, scientific modelling can be used as a decision support tool in choosing the most efficient control method or strategy.

This thesis describes the modelling of decision making in controlling FMD. This model can then be used to support decision makers. To do this, epidemiologic and economic models have been created. The epidemiologic model provides a description of FMD epidemic results with different control strategies. Epidemiologic criteria in decision making for selecting FMD-control strategy can be established using this epidemiologic model. The economic model presents a financial analysis of different FMD-control strategies. The financial evaluation of FMD-control strategies provides economic criteria for use in decision making for FMD-control strategies.

1.2 FMD in the Republic of Korea

FMD is one of the most important livestock diseases in terms of economic impact since it is a highly contagious disease capable of infecting cloven-hoof animals such as cattle, pigs, sheep, and goats (Thompson et al., 2002). The main impacts of FMD in terms of livestock industry are reducing milk yield in dairy animals, lameness in draught animals, abortions in breeding stock, or loss of weight in growing animals (Alexandersen et al., 2003). The economic impact of FMD results not only from the rapid spread of the disease and consequent loss of livestock production (Garner et al., 2002) but also from export bans for livestock products (Randolph et al., 2002). In addition, the most significant economic loss is from culling infected animals to prevent the spread of disease to nearby susceptible herds or farms (James and Rushton, 2002).

The Republic of Korea experienced an outbreak of FMD from November 2010 to April 2011 (MOSPA, 2011). The FMD virus strain of the outbreak belonged to the O serotype of the South-East Asian group and it affected pigs, cattle, deer, and goat farming systems. During the epidemic, the number of farms confirmed with FMD was 3748, comprising 1933 cattle, 1643 pig, 45 goat, and 43 deer farms. During the FMD epidemics, two main control strategies were implemented: culling of infected farms after confirmative diagnosis and pre-emptive slaughtering of all cloven-hoofed animals within a 0.5 kilometre radius of an infected farm. With 35 million depopulated animals, the 2010/11 FMD outbreak cost the national budget of the Republic of Korea about USD 2373 million (MOSPA, 2011).

1.3 Thesis aim and structure

The aim of this thesis is to describe scientific decision making in choosing strategies to control a transboundary livestock disease. To meet this primary goal, the 2010/11 FMD epidemic in the city of Andong, Republic of Korea was selected as an example of a contagious animal disease.

Decision making for an FMD-control strategy was investigated under three objectives:

1) Simulation model to evaluate the effectiveness of control measures during the 2010/11 FMD epidemic in the city of Andong, Republic of Korea;

2) Economic comparison between control strategies during the 2010/11 FMD epidemic in the city of Andong, Republic of Korea;

3) Scientific modelling of decision making for controlling FMD using results from simulation of epidemiologic and economic FMD spread results.

Data from the 20101/11 FMD epidemic in the Republic of Korea (MOSPA, 2011) were used to achieve these objectives.

The studies presented in this thesis are in the form of manuscripts prepared for publication. Therefore, some repetition of background information between each chapter may occur, especially in the introductory sections. However, the reference style has been standardized throughout the thesis to that of the journal *Preventive Veterinary Medicine*.

Chapter 2 presents a critical review of the background of decision making in choosing a transboundary livestock disease control strategy. The criteria needed to apply the decision analysis are investigated. It is useful to establish economic criteria in decision making since economic feasibility is one of the most important criteria in livestock industry. Therefore, an economic evaluation method to assess the cost efficiency of transboundary livestock disease control measure is also described. Advantages, disadvantages, applications, and limitations of the economic analysis are described. In addition to economic criteria, other criteria such as epidemiologic criteria and social-environmental criteria are also described.

Chapter 3, the first manuscript of the thesis, reports the importance of factors in choosing an FMD-control strategy from the perspectives of chief veterinary officers (CVOs) in the Asia-Oceania region. A questionnaire was designed to collect the preferences of CVOs and applied during the 28th conference of the OIE Regional Commission for Asia, the East and Oceania (OIE, 2013a). The resulting preferences were then converted to comparable measures. In addition, the difference in preferences between countries free from FMD and those having experienced FMD was also evaluated.

Chapter 4 describes an FMD simulation model in the city of Andong, Republic of Korea. Epidemiologic criteria in decision making for selecting FMD-control strategy could be established by using the simulation model. Simulation software, InterSpread Plus (ISP), has previously been used to simulate the spread of FMD between farms in the Republic of Korea (Yoon et al., 2006) and the United Kingdom (Morris et al., 2001; Thompson et al., 2002). The parameters needed to construct simulation models were collected based on the real FMD epidemic in the Republic of Korea in 2010. Parameters including demographic characteristics of population at risk and population size were used to make a spatial simulation model of FMD spread. The accuracy of the simulation model was assessed by comparing the results from the model to the real outbreak data. Results from this study provide parameters to evaluate the cost-effectiveness of FMD-control strategies.

Chapter 5 presents an application of cost-effectiveness analysis of FMD-control strategies in the city of Andong, Republic of Korea. The cost-effectiveness of FMD-control strategies was evaluated using the previous simulation model. Information about costs related to FMD-control strategies, such as movement restriction, pre-emptive slaughtering, or vaccination, was based on the data from the 2010/11 FMD epidemic in the city of Andong, Republic of Korea. Uncertainty and variability of input values in the analysis were measured by sensitivity analysis.

Chapter 6, the final study, uses results from chapters 5 and 6 to develop a scientific model of the decision making process in controlling FMD. Multiple criteria — epidemiologic, economic, and social-environmental — were identified through previous studies and questionnaire research. The objectives of this study were twofold: to develop an integral evaluation framework for decision making when choosing an FMD-control strategy, and to compare the preference of applying FMD-control strategies between different stakeholders. Different types of FMD-control strategies were ordered by scoring each strategy according to the preference of stakeholders. The perspectives of CVOs from different countries were assessed.

The thesis concludes with a discussion of study findings including limitations, identification of important factors in decision making process, plans for future study, and, finally, the contribution the thesis has made to providing better understanding of decision making in choosing animal disease control measure at different scales.

Chapter II

2 Literature review

2.1 Introduction

Decision making about the best strategy to control transboundary livestock disease, particularly foot-and-mouth disease (FMD) and classical swine fever (CSF), requires consideration of a number of areas including epidemiology, economics, politics and animal welfare (Cox et al., 2013). For example, when applying pre-emptive slaughtering as a control measure for FMD, decision makers need to consider the economic loss to farmers, the cost of slaughtering, negative impacts on environment due to burial of culled animals, and the concerns of the public for animal welfare. In addition, decision makers should consider the concerns of farmers whose livestock may not currently have the disease and who could lose income because their farms would be quarantined and by incurring costs through the implementation of biosecurity measures to reduce the likelihood of FMD introduction. It is not a straightforward process to compare these considerations using one single method, because these factors are measured on different scales. For example, the disease epidemic itself can be measured in a quantitative manner, such as the number of infected farms or animals, duration of epidemic, or the time until the country can be declared free of the disease; but the effect of the disease on farmers' mental health is measured in a qualitative manner using such things as subjective stress levels and depression index scores (Beck et al., 1988). Furthermore, stakeholders might have different preferences for factors when making decisions regarding disease control strategies.

Multi-criteria decision analysis (MCDA) is one framework that can be used to describe the different views and preferences of stakeholders in a manner that is rigorous, inclusive, defensible, and transparent (Gregory et al., 2012). MCDA provides a framework by which non-monetary factors can be combined with monetary factors without requiring the decision maker to assign a monetary value to all the factors, as is the case with social benefit-cost analysis. MCDA is an emerging area in veterinary science. Mourtis et al. (2010) applied MCDA to evaluate control strategies for CSF from the perspectives of chief veterinary officers (CVOs) in France, Germany, Great Britain, Hungary, Italy, and Poland. Cox et al., (2013) applied MCDA to prioritise infectious diseases associated with climate change in Canada. However, the technique is not new and has been used in environmental sciences for many years. According to Huang et al. (2012), 765 environmental sciences papers that applied MCDA were published on the Web of Science database between 2000–2009.

In addition to helping evaluate problems, MCDA is a tool that could be used to facilitate communication between the various stakeholders. In an outbreak, FMD can spread rapidly between susceptible animals; therefore, rapid implementation of control strategies is critical. One way to ensure control strategies are implemented quickly is to gain the support of stakeholders through communication with decision makers (Rweyemamu et al., 2008). The failure to rapidly implement control strategies due to communication failure was highlighted during the 2001 FMD outbreak in the Netherlands, where the government spent considerable time convincing farmers to adopt a pre-emptive slaughtering strategy (Pluimers et al., 2002).

Decisions regarding transboundary livestock disease control strategies are suitable for assessment using MCDA. An MCDA is often conducted as a multiple step process: 1) determining the decision making context, 2) identifying alternatives to be appraised, 3) determining the criteria, 4) measuring the criteria, 5) standardising the measurement, 6) determining criteria weight, 7) calculating overall scores and ranking, and 8) performing a sensitivity analysis (Gregory et al., 2012). This review will explore each of the steps in the MCDA process in more detail with specific reference to determining the best control strategy for transboundary livestock diseases.

2.1. Determining the decision making context

Transboundary livestock disease control strategies can be evaluated by comparing how well they minimise the negative epidemiologic, economic, and social-environmental impacts of diseases. The epidemiologic impact of disease can be measured as the number of infected animals, the size of outbreak area, and the duration of outbreak. Among these factors, the number of infected animals and the size of disease infected area have been frequently used to measure the epidemic’s impact. For example, Boklund et al. (2009) evaluated the effectiveness of CSF-control strategies in Southern Jultan, Denmark, using a simulation model to compare the number of CSF-infected animals and the duration of a CSF epidemic. In their study, the median number of simulated CSF-infected farms was four (range 1–29) for the European Union CSF-control strategies. These strategies consisted of the depopulation of CSF-infected farms, surveillance, and movement restriction in the study area. Similarly, for New South Wales and Queensland, Australia, Garner et al. (2011) created a simulation model to compare the number of equine influenza (EI) infected farms and the size of the EI-infected area when movement restriction was applied with and without vaccination. When vaccination was applied to all horse farms within a one kilometre radius of an EI-infected farm, the number of EI-infected farms was reduced by 60% compared to the number of EI-infected farms if no vaccination was applied.

The economic impacts of diseases are typically classified as either direct or indirect. Direct losses are those associated with mortality, reduced production, abortion, and delayed conception in breeding stock. Indirect losses are the restriction of livestock product exports to disease-free countries and reduced domestic purchasing of livestock products. Thompson et al. (2002) estimated the economic impact of the 2001 FMD epidemic in the United Kingdom at GBP 3.1 billion. In Australia, the decrease in gross domestic product due to an FMD outbreak has been estimated as approximately AUD 3.5 billion (Garner et al., 2002).

Not only does the choice of control measure have an epidemiologic and economic impact, it also has a major social impact. For example, pre-emptive slaughtering of livestock may affect the mental health of farmers and the public. During the 2001 FMD epidemic in the United Kingdom, the mental health of 54 rural citizens in Cumbria, where approximately 3,000 farms were depopulated, was surveyed for 18 months, from the end of the outbreak in December 2001 to June 2003 (Mort et al., 2005). For the respondents, life after the 2001 FMD epidemic was accompanied by distress, fear of a new disaster, and loss of trust in authority.

In addition to the social impacts, control measures can have impacts on the environment, as burying carcasses can contaminate ground water and burning carcasses results in air pollution. The negative impact of control measures on the environment can be measured by experimental studies. Yuan et al. (2013) studied contaminants from burial sites of cattle carcasses in the United States, finding several contaminants, including veterinary antimicrobials, monensin, steroids, hormones, and veterinary pharmaceuticals, near carcasses in burial sites; these might negatively impact the ground water near the burial site.

Decision makers involved in the control of transboundary livestock diseases need to consider epidemiologic, economic, and social-environmental impacts of a disease or of the control measures at the same time. MCDA can be used as a decision support tool for selecting the best control strategy by comparing the impacts of disease under different control strategies and ranking the strategies.

2.2. Identifying alternatives

Control strategies for transboundary livestock diseases rely on a combination of three principles: prevent contact between infectious and susceptible animals through movement restriction; eradicate the etiological agent by depopulation; and increase immunity in susceptible animals through emergency vaccination (Turner, 2011; Stevenson et al., 2013). This section of the literature review will consider each of the control strategies as well as the role of a surveillance system in control. Although surveillance systems are not a control strategy, they play an important role in disease control strategies and must be considered alongside control strategies, because decision makers may need to divert resources for control to surveillance.

2.2.1. **Movement restriction**

Transboundary livestock diseases such as FMD, CSF, or highly pathogenic avian influenza (HPAI) are transmitted between susceptible animals by various routes including direct and indirect contact. Direct animal-to-animal contact plays an important role in the spread of disease and occurs as a result of animal movements. Bates et al. (2001), estimated the movement frequency of dairy cattle according to the size of dairy farms in California, United States. According to their study, the mean number of movements per month was 2.6 for a farm with fewer than 1,000 cows, 1.6 for farms with between 1,000 and 1,999 cows, and 2.0 for farms with more than 2,000 cows.

Indirect contacts include contact between animals and people, animals and equipment, or animals and fomites (Ferguson et al., 2001). Contact between animals and people can occur as a result of artificial insemination, medical treatment, and hoof trimming. Contact between animals and equipment typically occurs when vehicles move between farms: for example, animal transporters, feed trucks and milk tankers. In Bates et al.’s (2001) survey of farms in California, the number of indirect contacts varied by farm type and size. The mean number of monthly indirect contacts was 22.1 for beef farms with fewer than 250 cattle and 46 for beef farms with more than 250 cattle. On dairy farms the mean number of indirect contacts in a month also increased with number of cattle. On dairy farms with fewer than 1000, 1000–1999, and greater than or equal to 2000 cattle, the mean number of monthly indirect contacts was 234, 418, and 743 respectively, while on pig farms the mean number of monthly movements was 98 for farms with fewer than 2000 pigs and 807 for farms with more than 2000 pigs.

The high frequency of indirect contacts reinforces the need for control measures to target people and vehicles. In the 2001 FMD epidemic in the United Kingdom, all livestock movements were banned and livestock markets closed for the duration of the epidemic (Ferguson et al., 2001). Kiss et al. (2006) noted that the initial spread during the 2001 FMD epidemic in the United Kingdom was attributed to the movement of sheep from farm to farm, farm to market, or market to farm during the silent spread period of the FMD epidemic. Similarly, during the 2010/11 FMD epidemic in the Republic of Korea, all livestock movements within a 20 kilometre radius of infected farms were strictly restricted (MOSPA, 2011). A road office, to check movement of live animals and animal products in and out of the FMD-infected area, was located on every route to or from the FMD-infected area. Movement restrictions during the FMD epidemics in the United Kingdom and Republic of Korea reduced indirect contact between FMD-infected animals and equipment or people. Thulke et al. (2011) demonstrated that the probability of CSF eradication in Denmark within one year was almost 100% when the efficacy of movement restrictions was higher than 90%.

2.2.2. **Depopulation**

Depopulation, also called slaughtering or culling, is a frequently used method to control transboundary livestock diseases by reducing the number of infected and susceptible animals in the population (OIE, 2013). The problem with depopulation is that the decision to cull infected or high risk susceptible animals often faces opposition from the public (Cohen et al., 2007). During the 2001 FMD epidemic in the United Kingdom, depopulation was regularly reported in the media, and the public criticized the government for what were perceived as cruel slaughtering methods (Crispin et al., 2002). Similarly, during the 2001 FMD epidemic in the Netherlands many farmers opposed the pre-emptive culling of animals that were not infected but at risk, even though this strategy was shown to be more effective than vaccination (Pluimers et al., 2002).

Depopulation has adverse impacts with respect to economic feasibility and the environment. The operational cost of depopulation is expensive because costs associated with slaughtering animals, disposal of feedstuff, cleaning and disinfection of farms, and disposal of carcasses can increase the total disease control cost. A benefit-cost analysis of depopulation as an FMD-control strategy in California (Bates et al., 2003a) showed that the economic efficacy of vaccination was better than that of depopulation; the benefit-cost ratio of depopulation with a five kilometre radius was 0.05 whereas the benefit-cost ratio of vaccination with the same radius was 10.1. Disposal of culled animals can also have a negative impact on the environment due to ground and surface water pollution. Delgado et al. (2010) identified more than 1300 chemicals that could be released into the environment when burning or burying carcasses and that could be harmful to human and animal health. These chemicals included ammonia, phosphate, formaldehyde, phenols, methane, and benzene.

Despite the economic and social-environmental issues associated with depopulation, it remains as an important disease control measure. The efficacy of depopulation as a transboundary livestock disease control strategy has been frequently evaluated (Bates et al., 2003c; Woodroffe et al., 2008; Tildesley et al., 2009; Lu et al., 2010; Thulke et al., 2011; Boadella et al., 2012). For example, Bates et al. (2003c) constructed an epidemiological simulation model of FMD spread to evaluate the efficacy of depopulation in California. According to the model, the median number of simulated FMD-infected farms decreased from 43 to 35 when the radius of the depopulation area increased from one to five kilometres. Similarly, Tildesley et al. (2009) reported that if depopulation had not been carried out during the 2001 FMD epidemic in the United Kingdom, the duration of the FMD epidemic might have been 345 (range 229–529) days rather than the actual 220 days.

2.2.3. **Emergency vaccination**

The European Union conference on FMD in December 2001 considered that an emergency vaccination can be applied as an alternative to a depopulation strategy (Scudamore and Harris, 2002). The term ‘emergency vaccination’ with respect to controlling transboundary livestock diseases is used to differentiate it from routine vaccination which means

> “*the successful immunisation of susceptible animals through administration, according to the manufacturer’s instructions and the Terrestrial Manual*” (OIE, 2013).

Emergency vaccination is applied during the disease outbreak to boost the immunity of susceptible animals. Emergency vaccination can be used in a country that either does or does not routinely vaccinate animals. For instance, the Republic of Korea had not routinely vaccinated susceptible animals against FMD, but during the 2010/11 FMD outbreak the decision was made to undertake emergency vaccination of all FMD-susceptible animals in the country because the disease was spreading rapidly (Park et al., 2013).

Emergency vaccination is also applied as either ‘vaccination to die’ or ‘vaccination to live’. Vaccinated animals are culled in ‘vaccination to die’ and are not culled in ‘vaccination to live’. Hagerman et al. (2013) used a simulation model to examine the effectiveness of ‘vaccination to die’ for controlling FMD in California, and showed it could reduce the number of infected farms requiring depopulation. The simulated median number of culled farms was 7700 if all FMD-susceptible animals within a 10 kilometre radius of FMD-infected farms were vaccinated and 8700 without vaccinating animals. Boklund et al. (2013) also used a simulation model to evaluate the effectiveness of ‘vaccination to live’ and ‘vaccination to die’ for FMD control in Denmark. When vaccination was not used the simulated median duration of an outbreak was 80 (range 5–255) days; in contrast, the simulated median duration of the FMD outbreak decreased to 59 (range 5–141) days for ‘vaccination to live’ and 53 (range 5–125) days for ‘vaccination to die’.

2.2.4. **Surveillance**

In general, a surveillance system is designed to demonstrate the absence of disease or infection, determine the presence or distribution of disease, or detect exotic or emerging disease. During a disease outbreak, a surveillance system aims to detect a disease as early as possible. By detecting disease earlier, control strategies can be applied more rapidly, reducing the size of the outbreak. There are two types of surveillance systems, based on how data are collected: passive and active surveillance (OIE, 2013). Passive surveillance depends on the reporting of disease suspect animals by farmers or veterinarians. In contrast, active surveillance uses surveillance teams to collect disease data. Passive surveillance requires fewer resources than active surveillance because the data are collected by local farmers or veterinarians (Rautureau et al., 2012), but active surveillance is resource intensive because a surveillance team consists of veterinary and public officers and visits areas at high risk, such as saleyards or abattoirs, to collect the disease data (Tambi et al., 2004). Generally, both surveillance systems are run concurrently to improve the cost-effectiveness of the surveillance system and likelihood of disease detection. The effectiveness of surveillance systems to reduce the impacts of disease has been evaluated in previous studies. Klinkenberg et al. (2005) used a simulation model to evaluate the effectiveness of the Netherlands' CSF surveillance system. In their study, a surveillance system with two-weekly inspections of CSF-susceptible pig farms reduced the duration of a CSF outbreak by six days compared with a surveillance system with four-weekly inspection.

2.3. Determining the criteria

When conducting an MCDA, decision makers evaluate alternatives systematically using predetermined criteria. In the context of control strategies for transboundary livestock diseases, the criteria can be classified as epidemiologic, economic, or social-environmental (Mourits et al., 2010). The epidemiologic criterion is related to the effectiveness of control strategies to eradicate or control the disease outbreak. The economic criterion includes the cost of the control strategies and the impact of disease on the whole economy. The social-environmental criterion considers the social impact of a disease outbreak, such as the mental health of affected farmers, and the environmental impact, such as environmental pollution due to the burning of carcasses.

2.3.1. **Epidemiologic criterion**

The epidemiologic effectiveness of disease control strategies can be evaluated by measuring the duration of the disease outbreak, the number of infected farms and animals, or the number of depopulated farms. Klinkenberg et al. (2005) constructed a simulation model to compare the duration of a CSF outbreak when different surveillance strategies were used. In their model, the simulated median duration of CSF outbreak was 58 days with a four-weekly inspection of pig farms for the presence of clinical signs of CSF, with surveillance beginning in the absence of disease in the Netherlands. Enhanced surveillance to include histological inspection of tonsils once CSF was detected shortened the duration of the outbreak by 23 days. In another example, Boklund et al. (2009) used simulation modelling to evaluate the effectiveness of CSF-control strategies in Southern Jutland, Denmark. In their study, the median number of simulated CSF-infected farms was eight (range 1–248) when CSF-infected farms and all pig farms within a 500 meter radius of a CSF-infected farm were depopulated. Similarly, Garner et al. (2011) evaluated the effectiveness of vaccination for control of equine influenza (EI) in Australia. According to their study, vaccinating all equine farms within a one kilometre radius of all EI-infected farms could reduce the number of EI-infected farms by 63.6% and the size of the EI outbreak area by 9.2% compared with simulated control strategies without vaccination.

In addition to the number of infected farms, the duration of the outbreak and the number of depopulated farms can be used to measure the epidemiologic criterion. Yoon et al. (2006) simulated the number of depopulated farms, including farms depopulated because of FMD-infection or pre-emptive slaughtering, in Anseong, Republic of Korea. The simulated median number of depopulated farms was 624 (range 316–2354) with pre-emptive slaughtering of all cattle and pigs within a five kilometre radius of an FMD-infected farm and 917 (range 316–2354) within a 0.5 kilometre radius. Historically, decisions regarding disease control have been based on outcomes from epidemiologic modelling (Willeberg et al., 2011). However, basing decisions on the epidemiologic criterion alone may not account for all options; thus other criteria, such as economic or social-environmental, should be considered.

2.3.2. **Economic criteria**

The economic effectiveness of disease control strategies can be evaluated by indicators such as the operational cost of control measures, farm losses due to the disease infection, or industry losses due to a disease outbreak. Economic analysis, such as benefit-cost analysis or cost-effectiveness, can quantify the costs associated with the disease control strategy. For example, Boklund et al. (2013) quantified the operational cost of FMD-control strategies in Denmark using a benefit-cost analysis. According to their simulation study, the estimated cost for a basic FMD-control strategy comprising depopulation of FMD-infected herds and a national standstill of animal movements for three days was EURO 665 (range 399–1137) million, whereas the cost for vaccinating all FMD-susceptible animals within a one kilometre radius of FMD-infected farms was EURO 573 (range 400–803) million and the cost for slaughtering FMD-susceptible animals within a 1.5 kilometre radius of FMD-infected farms was EURO 548 (range 393–800) million. Bates et al. (2003a) applied a cost-effectiveness analysis to estimate the indemnity cost for depopulated farms due to FMD-infection in California; the indemnity cost for a typical dairy farm of 884 cows was around USD 2.6 million, including compensation paid to farmers for culled animals. Similarly, Thompson et al. (2002) estimated the indirect loss due to the 2001 FMD epidemic in the United Kingdom. In their study, the loss to the UK's tourism industry because of a reduction in numbers of tourists during the epidemic ranged from GBP 2.7 to 3.2 billion.

2.3.3. **Social-environmental criteria**

Disease control strategies for transboundary livestock diseases have a wide-ranging impact on society. The social implications of disease control strategies can be evaluated by measuring indicators such as the mental and physical health of people, particularly those directly affected by the outbreak. For example, the mental health of 661 dairy farmers was measured in the Netherlands after the 2001 FMD epidemic (Van Haaften et al., 2004). According to that study, farmers whose livestock were culled to control the outbreak had 'post-traumatic stress at levels requiring professional help'. The risk of post-traumatic stress was 5.78 times higher for farmers whose livestock were culled than for farmers whose livestock were not culled.

Another issue for consideration when evaluating control options is the physical health of people. For example, formaldehyde, which is used frequently as a disinfectant during an FMD outbreak, may cause various side effects such as irritation, redness, difficulty breathing, or tightness in the chest (de Groot et al., 2009). Furthermore, formaldehyde is classified as a probable human carcinogen under conditions of high exposure (Higginson and DeVita, 1980). Burning as a disposal method of carcasses can also release toxic substances, such as dioxin, and it may affect human health. The Cumbria FMD panel (Cumbria Foot and Mouth Disease Inquiry Panel., 2002) recorded the level of dioxins, a probable carcinogen (Bertazzi et al., 2001), within two kilometres of pyre sites as being higher than the typical background level during the 2001 FMD outbreak in Cumbria, United Kingdom.

In addition to the social impact of disease control strategies, their environmental impacts should also be considered. The environmental impact of disease control strategies can be evaluated by measuring criteria such as ground and air pollution due to disposal of carcasses. For instance, Yuan et al. (2013) examined contaminants in discharges from buried carcasses. They found that residues such as veterinary antimicrobials or monensin could be potential contaminants in the soil near buried carcasses. Air pollution is another environmental effect of disease control strategies. During the 2001 FMD epidemic in the United Kingdom, people near the burning area were bothered by the odour (Scudamore et al., 2002). In addition, Lowles et al. (2002) found that while carcasses were burnt in Cumbria during the 2001 FMD epidemic, the level of dioxin in the air was 7×10^{-18} kg/ m^3; this was more than 20 times higher than the background level of dioxins.

2.4. Measuring the criteria

In order to conduct an MCDA to evaluate control strategies for transboundary disease we must measure the criteria. This part of the review details the methods used to measure epidemiologic, economic, and social-environmental criteria when evaluating control strategies for transboundary disease of livestock. During an actual disease outbreak, it is not feasible to apply different control strategies in order to evaluate effectiveness. Thus, simulation modelling is frequently used to determine the likely course of a disease outbreak under different control strategies. Furthermore, the results from a simulation model can be used to measure economic or social-environmental criteria.

2.4.1. Methods to measure the epidemiologic criterion

The epidemiologic impact of transboundary livestock disease control strategies is commonly measured by using indicators such as the number of infected farms and animals, the duration of disease outbreak, or the size of disease outbreak area. Epidemiologic modelling has been frequently used to simulate disease outbreaks. The World Organisation for Animal Health (OIE) surveyed 100 member countries in 2010 and found 49% of respondents were using epidemiologic models in animal diseases contingency plans (Willeberg et al., 2011). From this survey, 92% (47/51) of respondents who had not used models reported they would like to develop models for disease contingency planning for their countries. Epidemiologic models of FMD-control strategies have been developed to support decision making in Australia (Garner and Beckett, 2005), New Zealand (Sanson et al., 2011; Stevenson et al., 2013), the Republic of Korea (Yoon et al., 2006), the United Kingdom (Morris et al., 2001), and the United States (Bates et al., 2003b; Carpenter et al., 2011).

Garner and Hamilton (2011) proposed ten steps for building epidemiologic models of transboundary livestock diseases. The first step of epidemiologic modelling is to define the objectives and configure the scope of the model (Step 1). For example, an epidemiologic model has been used to evaluate the effectiveness of disease control strategies for CSF in Denmark (Boklund et al., 2009) and for FMD in the Republic of Korea (Yoon et al., 2006) and the United States (Bates et al., 2003b; Harvey et al., 2007). All these studies used the number of infected farms and the duration of the outbreak as a means of comparing effectiveness of different FMD-control strategies. Boklund et al. (2009) also considered the number of slaughtered animals when comparing control options. On balance it would be reasonable to say that the most efficient control strategy in the perspective of epidemiology is typically the one with the shortest duration of disease outbreak, or the fewest disease infected animals or farms.

The second step in developing an epidemiologic model is to collect data about the susceptible population, the epidemiology of the disease, and the efficiency of the control strategies (Step 2). When available, national statistics of animal numbers are a good source to for determining the distribution of susceptible animals. Information about the disease in question (e.g. incubation period or the infectious period) can be acquired from disease outbreak history or experimental studies. Mardones et al. (2013) used meta-analysis to aggregate the results of 55 trials in which susceptible animals were infected with FMD virus; they showed the infectious period for cattle was best described using a Gamma distribution (α=3.969, β=1.107), while the same state in pigs would be best described by a Log logistic distribution (γ=0, β=5.39, α=5.474). Experimental studies can also be used to determine the likely efficiency of disease control measures, as was done by Halasa et al. (2011), who used a meta-analysis of 28 experimental studies to measure the FMD vaccine efficacy for livestock animals. Compared to non-vaccinated animals of the same species, the risk of FMD infection for vaccinated animals was 0.71 (range 0.59–0.85) times lower in cattle, 0.67 (range 0.51–0.87) times lower in pigs, and 0.59 (range 0.44–0.80) times lower in sheep. Another option is to combine field experience with experimental studies, as was done by Garner et al. (2011). In that study, field experience obtained during the 2007 Equine Influenza (EI) outbreak data in Australia was combined with experimental studies that determined how vaccinated horses were infected.

The third step in constructing a simulation model to compare control strategies is to develop a conceptual model (Step 3). Conceptual models are typically a visual or verbal description of the problem that links the internal variables to model outputs. Cognitive maps provide a means of describing the relationships between variables in a visual manner that can be understood by others (Walshe and Burgman, 2010). To construct cognitive maps the key concepts are selected and the relationship between concepts specified. Key concepts of conceptual models are expressed as nodes, which are main points of the cognitive maps; relationships between concepts are expressed as lines. Lines between nodes in cognitive maps visualize causality using arrows and strength using letters such as weak (w), moderate (m), or strong (s). An example of a cognitive map is the one used to explore concepts with experts around the control of Australian bat lyssavirus (Walshe and Burgman 2010). In this cognitive map the key concepts included 'immediate post-exposure treatment', 'rabies immunoglobulin' and 'number of deaths', and the relationships between these concepts were visualized using nodes, lines and arrows.

The fourth step is to validate the conceptual model; that is, to determine whether the theories and assumptions in the conceptual model are appropriate (Step 4). The process of validation for an infectious disease model requires the opinions of experts such as veterinarians and epidemiologist and may be supported by a review of relevant literature. Sometimes it can be useful to include non-technical industry stakeholders. Including people from industry is especially useful when trying to understand transmission pathways associated with illegal pathways. For example, an Australian study used focus groups and unstructured interviews to explore swill feeding practices and disease knowledge among peri-urban pig producers (Schembri et al., 2010). Sometimes stakeholders will disagree with the framework for the conceptual model, and it is useful to explore these differences. Typically this will be done informally via meetings and workshops; however, it is possible to explore differences more quantitatively, as was done by Walshe and Burgman (2010) when exploring differences in conceptual models constructed by experts to describe control options for Australian bat lyssavirus.

In order to evaluate the epidemiologic criterion the conceptual model must be converted to a quantitative model (Step 5). The conversion can be done using various programming languages such as Java (Sun Microsystem Inc., Santa Clara, California), R (R Core Team, Vienna, Austria), or a Microsoft Excel spreadsheet (Microsoft Corporation, Washington, United States). Several programs have user-friendly interfaces that enable users without knowledge of a programming language to construct epidemiological models for infectious disease; for example, AusSpread (Garner and Lack, 1995), InterSpread Plus (Stevenson et al., 2013), and the North American Animal Disease Spread Model (Harvey et al., 2007), all of which are stochastic state transition modelling programmes.

The next steps are verification of the model (Step 6) and checking operational validity (Step 7). Verification involves checking that mathematical equations, formulae, or computer algorithms are operating as intended. Verification is typically done by running a model with different inputs to ensure that the model's results are consistent with a conceptual model. Operational validity is more complex and involves comparing the model to real conditions. Sanson et al. (2011) evaluated the contact component of their model by comparing predicted movements to real dairy cow movement information recorded in Ontario, Canada.

When data are not available to assess operational validity then the model may be assessed by comparing results to those obtained from another model. The simulation programs AusSpread, InterSpread Plus, and North American Animal Disease Spread Model were all validated by comparing simulated outputs (Sanson et al., 2011). The validation involved running 40 iterations of five identical scenarios; namely, an FMD outbreak with no controls, standard EU controls, standard EU controls plus 0.5 kilometre contiguous cull, and standard EU controls plus vaccination at eight and 21 days. Comparison of the simulated results found that the programs varied in the absolute number of FMD-infected farms and outbreak duration. However, for each measure of efficiency (e.g. number of infected properties), the rank order of control options was identical. For example, early use of ring vaccination resulted in the largest drop in the number of infected premises for all models.

All epidemiologic models have uncertainty because there is uncertainty in the data collected in biological systems (Kitching et al., 2006; Carpenter, 2011). The importance of uncertainty on model outputs can be assessed by sensitivity analysis (Step 8). Sensitivity analysis is performed by changing input values of parameters in the model and comparing the results to those of the default model. Unlike the verification of the model (Step 6), the purpose of changing input values in sensitivity analysis is to measure the impact of parameters on the results. If the model's results are sensitive to the parameters that have a high degree of uncertainty, then the validity of the model decreases. Owen et al. (2011) performed a sensitivity analysis on the New Zealand Standard Model, which is an epidemiologic model of an FMD outbreak in New Zealand. In this, the value assigned to a model input was changed while holding other values unchanged. For example, the input value for the detection probability of surveillance in the Standard Model was 0.5, which was changed to a Uniform distribution (0, 1) in the sensitivity analysis without changing any other model parameters. The process was then repeated for other input parameters. To describe the effect of a model input on the simulation results, a partial rank correlation coefficient was calculated. This analysis showed that the inputs having the greatest impact on the simulation results were the number of movements between farm and saleyard, and the detection probability for active surveillance. Specifically the partial rank correlation coefficient between the number of infected farms and the movement parameter was 0.56 and the active surveillance parameter was 0.26.

After reducing the model's uncertainty, an epidemiologic model can be used to investigate disease spread and the effectiveness of control measures (Step 9). The constructed model can provide various scenarios of disease transmission in different circumstances. When Bates et al. (2003b) applied an epidemiologic model to simulate FMD spread under different FMD-control strategies in

California, they found the simulated median duration of an FMD outbreak was 69 (95% confidence interval (CI) 25–109) days for movement restriction, 57 (95% CI 26–88) days for vaccinating farms within a five kilometre of an FMD-infected farm, and 57 (95% CI 27–85) days for slaughtering farms within a five kilometres of an FMD-infected farm.

Finally, the results from the model are interpreted (Step 10). These are interpreted in the context of what the conceptual model was, how the conceptual model was implemented, and what limitations or assumptions the model included. The limitations and assumptions require careful consideration when interpreting the results. For example, if there was no available information on the frequency of animal movements, then the model may assume a particular input value of animal movements. The interpretation of the model results should then be prefaced with 'if animal movement occurred at this frequency then we would expect this outcome…'

2.4.2. **Methods to measure the economic criterion**

The economic impacts of transboundary livestock disease control strategies are divided into two types: direct and indirect. The direct impact of a disease outbreak focuses on individual sectors in the economy. For example, animal products loss, such as culling infected animals or destroying infected feed stuff, is a direct impact. The indirect impact focuses on all sectors of the economy associated with the disease outbreak. For instance, losses associated with the ban of exporting animal products and decreases in the number of tourists are indirect impacts. The methods used to measure direct and indirect impacts vary; therefore, this section will separately address the different methodologies commonly used to measure the direct and indirect impacts associated with control of transboundary diseases.

2.4.2.1. Methods to measure direct impacts

Microeconomic impacts for transboundary livestock diseases are commonly assessed using either a benefit-cost analysis (BCA) or cost-effectiveness analysis approach (Rushton, 2009). In cost-effectiveness analysis, the disease control strategy with least cost is considered the best option. BCA considers costs in relation to the benefits that maybe accrued. In practice, however, benefits are limited to the saved costs if eradication or control is successful. Consequently, when measuring the direct impacts of transboundary disease there is little difference between a BCA and a cost-effectiveness analysis as long as the outcome, such as eradication, occurs for all alternatives.

An eight step framework has been proposed for performing a BCA (Anomymous, 2006). The first step, as with modelling the epidemiologic criterion, is to define the scope and objectives of the analysis. Economic analysis has been used to evaluate the economic effectiveness of strategies for control of CSF in Denmark (Boklund et al., 2009) and for FMD in the Netherlands (Berentsen et al., 1992), United Kingdom (Thompson et al., 2002), and United States (Bates et al., 2003a). All these studies determined the costs of control strategies, such as the cost of culling, rendering, cleaning, blood tests, vaccination, or compensation for culled animals. In each case the strategy with the lowest cost was considered the most economically efficient option.

The second step in a BCA is to ensure that all alternatives being considered are feasible by identifying any constraints in meeting the objectives. The constraints can be financial, institutional, environmental, and political (Anomymous, 2006). In the context of evaluating control strategies, a constraint might be that the control option is capable of controlling the disease within a specified period. Another constraint might be that strategies do not cost more than a pre-determined amount.

Having defined the objectives and detailed any constraints, the next step in a BCA is to develop a list of alternatives. Alternatives for evaluating economic effectiveness are different disease control strategies. In some cases, it may be useful to include a ‘do nothing’ option, where the economic effectiveness of a control strategy is evaluated compared to what would have happened had the control strategy not gone ahead. A ‘do nothing’ option may be appropriate for diseases that authorities may not wish to control because the required cost is too large but the prevalence of disease is very low (e.g. EI and porcine respiratory and reproductive syndrome). However, for epidemics of FMD and CSF in a country previously free of these diseases, the ‘do nothing’ option will not be considered. Rather, the baseline in this situation may be the cost of an actual response to an outbreak. If there has not been a recent outbreak, the baseline scenario will be the country’s planned response. In Boklund et al.’s (2009) study, the baseline strategy for control of CSF in Denmark was the European Union (EU) mandatory strategy, which consists of depopulation of CSF-infected farms, movement restriction within a three kilometre radius of CSF-infected farms, and surveillance within a ten kilometre radius of CSF-infected farms. The economic effectiveness of other additional strategies such as vaccination was then compared to the EU mandatory strategy.

The next step in the economic analysis is critical and involves identifying and quantifying the economic impacts of the control strategy. If there has been a disease outbreak then the cost information from the outbreak can be used. For example, Thompson et al. (2002) estimated the cost of an FMD outbreak at GBP 3.1 billion, using information from the 2001 FMD epidemic in the United Kingdom. The estimate was based on the costs of control measures such as slaughtering, disposal, cleaning or disinfection, and the number of FMD-infected or depopulated farms during the epidemic. If there is no history of disease, national economic statistics or expert opinion are used to quantify the cost of disease control strategies. Bates et al. (2003a) estimated costs for pre-emptive slaughtering for the control of FMD in California, using an epidemiologic model to determine key parameters such as number of infected and depopulated farms. They combined the simulated results with indemnity costs obtained from the actual indemnity cost paid for eradicating *Mycobacterium tuberculosis* in 2002. The cost was around USD 70 million for slaughtering FMD-susceptible animals within a five kilometre radius of an FMD-infected farm. Boklund et al. (2009) estimated the costs of different CSF-control strategies in Denmark based on the opinions of meat workers, pig producers, veterinarians, and public officers. An epidemiologic model was also constructed to simulate potential CSF spread under different CSF-control strategies. The simulated median cost was EURO 133 (range 124–147) million for depopulating CSF-susceptible animals within a one kilometre radius of a CSF-infected farm and EURO 223 (range 207–237) million for vaccinating and slaughtering vaccinated animals within a one kilometre radius of a CSF-infected farm.

The fifth step is to assess the economic feasibility of alternatives. In BCA, results are summarised by computing outputs that can be compared, such as net present value, benefit-cost ratio, or internal rate of return. Net present value is the difference between the sum of discounted cost and the sum of discounted benefit. If the net present value of one control strategy is larger than the others then the control strategy is the most economically feasible among the alternatives. Benefit-cost ratio is the ratio of the sum of discounted benefits to the sum of discounted costs. If the benefit-cost ratio of a control strategy is larger than one, the control strategy is economically feasible. Internal rate of return is the rate that will make the net present value equal to zero. If the internal rate of return exceeds the pre-defined discount rate, the control strategy is economically viable. In Bates et al. (2003a), net present value and benefit-cost ratio were used to evaluate the economic feasibility of FMD-control strategies in California. Net present value and benefit-cost ratio for vaccinating FMD-susceptible animals within a five kilometre radius of an FMD-infected farm were around USD 18 million and 10.1, respectively; for depopulating FMD-susceptible animals within the same area, these were around negative USD 458 million and 0.05, respectively.

The sixth step is a ‘sensitivity analysis’ to assess the impact of variables with uncertainty on the economic analysis results. The input value of variables with uncertainty is changed and the results compared to results from default input values. For example, in their study for evaluating the cost-effectiveness of FMD-control strategies in California, Bates et al. (2003a) performed a sensitivity analysis to estimate the impact of increasing the cost of herd vaccination by 30%. Despite the increased vaccination cost, vaccination was economically feasible because the net benefit of vaccinating all FMD-susceptible animals within five kilometres of an FMD-infected farm was around USD 16 million compared to negative USD 458 million for slaughtering all animals within five kilometres of an FMD-infected farm.

After evaluating the uncertainty of variables, the seventh step is to consider the equity and distributional implications of each strategy. When considering the equity for disease control consideration must be given to who is paying the costs for control strategies. For example, when depopulation and movement restriction are applied in an infected area, farmers whose animals are culled are paid compensation by the government. However, farmers whose animals are not depopulated but whose movement is restricted will experience economic hardship because they are not compensated. Issues related to equity might not be addressed by economic analysis because the most economically efficient control strategy is not always good for all stakeholders. MCDA can deal with the equity issues of a disease control strategy by expressly considering equity as a stakeholder preference.

The final step is to report the results and prepare a recommendation. It is important to highlight the assumptions used in forecasting the economic effectiveness of control strategies. The critical assumptions should appear at the beginning of the report. Disease control strategies are ranked according to their economic effectiveness to make a recommendation.

2.4.2.2. Methods to measure the indirect impacts

Decision makers need to consider not just the cost of control but the impact of disease on the whole economy (i.e. indirect impacts) from factors such as disrupted trade. Simple BCA or cost-effectiveness analyses are not well suited to estimating indirect impacts. The best approach to measure indirect effects is to use an input-output analysis or general equilibrium analyses, which quantify the flow of inputs between sectors in the economy. For example, an FMD will not only reduce animal products and employment of meat workers but will also reduce employment in the tourism sector because tourists avoid visiting a country during an FMD outbreak.

Input-output analysis and general equilibrium analyses are concerned with the behaviour of the economy as whole rather than individual sectors within the economy. This means when investigating different control options they only need to be considered separately if their impacts on the economy as a whole will differ. For example, indirect impacts would differ if the duration of the disease outbreak was less under one control option compared to another. This means prior to constructing an input-output model the controls need to have been evaluated using an epidemiologic model to estimate the duration of the outbreak. Having determined if different scenarios will be required, an input-output analysis follows steps similar to those of economic analysis: define objectives, identify constraints, quantify inputs and outputs, conduct a sensitivity analysis, and report the results. There have been few examples of input-output analysis and general equilibrium analyses for disease outbreaks when evaluating control strategies for transboundary disease. One reason for this may be that the information required for performing the input-output analysis requires a large amount of information.

In general, the objective of input-output analysis and general equilibrium analyses for transboundary livestock disease is to quantify the impacts on the entire economy. Previous work has used input-output models to quantify the impacts of FMD outbreaks on the economies of Australia (Garner and Lack, 1995) and the United Kingdom (Thompson et al., 2002; Pendell et al., 2007).

The second step in input-output analysis is to identify the sectors of the economy that would be affected by a disease outbreak. In the context of a transboundary disease these include agriculture, grain farming, hospitality, fishing and hunting, transportation, meat wholesale trade, supermarket trade, and food service. In the study of Thompson et al. (2002), the indirect impact of the 2001 FMD epidemic in the United Kingdom was measured using aspects of agricultural industry and tourism.

The third and critical step in the input-output analysis is to quantify the flow and relationships between different sectors of the economy. For example, a decrease in supply of milk due to depopulation of FMD-infected dairy farms results in a brief reduction in demand for supplementary feed, which may have a longer term effect on supply in the next year. Data for an input-output model, just as with a BCA, can be obtained from information about a previous disease outbreak, national economic statistics, and expert opinion. Thompson et al. (2002) used national economic statistics to estimate the indirect impact of the 2001 FMD epidemic for agricultural and food industry in the United Kingdom. The reduction in the agricultural industry resulted in losses across the food industry, from abattoirs and auction houses to meat processors. Thompson et al. (2002) estimated that these losses cost the agricultural sector GBP 355 million and the food industry GBP 170 million. Mahul and Durand (2000) estimated the indirect impact of an FMD epidemic in the agricultural industry in France under different FMD-control strategies. Their model estimated the period of exclusion from international markets, based on the simulated duration of FMD outbreak under different scenarios. Information regarding the quantity of animal product exports and related costs was obtained from meat workers and animal product merchandisers. To estimate the cost, the quantity exported per day was multiplied by the period of the export ban. The cost to the agricultural sector was estimated at FRF 1252 million for depopulating FMD-infected farms and FRF 1840 million for vaccinating FMD-susceptible animals within a five kilometre radius of an FMD-infected farm.

Before reporting results it is essential that a sensitivity analysis be conducted to evaluate the impact of variables on the results. A sensitivity analysis is performed by changing the input values of variables and comparing the results to the results with default value; that is, it is the same as the method used when evaluating an epidemiologic model or in a BCA. Sensitivity analyses can also be considered ‘what if’ scenarios that may help decision makers decide between options under uncertainty. For example, Thompson et al. (2002) performed a sensitivity analysis in their estimation of the cost for the 2001 FMD epidemic in the United Kingdom. If their export market did not recover for a further seven months, the cost for the agricultural industry was increased by GBP 95 million, from GBP 355 to GBP 450 million.

The final step is to report the results of an input-output analysis and general equilibrium analyses. The report should include the full list of industries affected by the disease outbreak and the amount of input and output between the industries. Limitations and assumptions must also be described in the report.

2.4.3. **Methods to measure the social-environmental criterion**

An outbreak of transboundary livestock disease impacts on society and the environment. Farmers whose farms are infected may experience hardships such as financial loss and the sorrow of losing animals, and may suffer from mental problems such as depression or stress. The public may voice concern about animal welfare issues, especially if pre-emptive culling (i.e. culling of healthy animals) is widespread. In addition, disposal of carcasses by methods like burning or burying may have negative impacts on the environment. This part of the review explores how to measure the social-environmental impacts of disease outbreaks.

2.4.3.1. Methods to measure the social impact

The social impact of transboundary livestock disease can be measured by determining the impact of a disease outbreak on the mental or physical health of people. The mental health of people affected or not affected by an outbreak of FMD is related to the disease outbreak size, such as the number of infected farms. In order to determine the social impact of disease we can examine the impact of disease outbreaks and controls where outbreaks have occurred. Van Haaften et al. (2004) surveyed the mental health of 661 dairy farmers during the 2001 FMD epidemic in Denmark. Among 661 participants, 215 were from areas where livestock were slaughtered (culled area); 242 were from areas where livestock had not been slaughtered but other FMD-control strategies, such as movement restriction, were applied (buffer area); and 204 were from FMD-free areas. The degree of depression was scored using the Beck depression inventory (BDI), which is a 21-item self-rating scale of depression in which each item was scored from 0 to 3 — the higher the score, the worse the depression status (Beck et al., 1988). Mean scores were highest for farmers in the culled area while farmers in the buffer and FMD-free area had similar scores. Physical health is also related to the size of the disease outbreak. Carcass disposal workers may be harmed by some of the veterinary medicines or disinfectants used to control diseases; for example, formaldehyde, which is used frequently as a disinfectant, may cause side effects such as irritation, redness, difficulty breathing, or tightness in the chest (de Groot et al., 2009).

2.4.3.2. Methods to measure the environmental impact

Control of transboundary disease that involves culling will have an impact on the environment because the carcasses must be disposed of, and during an outbreak this may need to occur rapidly. If the carcasses are buried then there is potential for soil or ground pollution. In a study in the United States, Yuan et al. (2013) constructed carcass burial pits to measure the concentration of contaminants from carcasses; these burial sites showed relatively high concentrations of veterinary antibiotics, carbon, and steroid hormones compared with other agricultural waste sites. Burning carcasses may not be a viable solution as this will result in air pollution. Lowles et al. (2002) monitored the concentration of air pollutants from a pyre during the 2001 FMD epidemic in Cumbria, United Kingdom, and found levels of pollutants such as sulphur dioxide, dioxins, furans, and polycyclic aromatic hydrocarbons were elevated above the typical background level of the area.

As with the social impact of a disease outbreak, environmental impact is related to the size of the outbreak. If the number of depopulated animals increases, the environmental impact will be worse. An epidemiologic model is valuable for simulating the size of the disease outbreak under different disease control strategies. Simulated control strategies that result in the fewest depopulated farms may cause the least impact on the environment.

2.5. Standardising the measurement (Scoring)

When conducting an MCDA, values given to each criterion are typically expressed on different scales. Indicators of the epidemiologic criterion might include the number of farms with infected animals or the duration of the disease outbreak, and an indicator of the economic criterion might be compensation paid to farmers. Before these indicators can be combined into a single score to compare strategies, the values must be converted to the same scale. Transformation of measurements to a standard scale is called standardization (Hwang and Yoon, 1981). In MCDA, several methods are commonly used to standardize values: 1) z-score procedure, 2) zero to one scoring procedure, and 3) maximum score procedure.

2.5.1. **Z-score procedure**

The z-score procedure standardizes the measurement by taking the mean and standard deviation of the measurements (Hwang and Yoon, 1981).

$$x'_i = (x_i - \overline{x_i}) \, / \, SD_i \quad \text{(Equation 2.1)}$$

Where x'_i : standardized score of alternative for the ith indicator, x_i : measurement of alternative for the ith indicator, $\overline{x_i}$: mean of the measurements of all alternatives for the ith indicator, and SD_i : standard deviation of the measurements of all alternatives for the ith indicator.

There are no examples of using the z-score procedure to standardise scores in the veterinary field. However, the z-score procedure can be used outside the MCDA framework to compare performance between alternatives. For example, Lindig (1998) applied the z-score procedure to standardize dioxin measurements at 90 different laboratories in Germany. In that study, laboratories were considered proficient if they exceeded a z-score threshold of 0.75. Sixty-eight out of 90 laboratories met the qualification of dioxin measurement based on the z-score.

The z-score procedure assumes the variable follows a normal distribution. However, when an epidemiologic model is used to simulate the disease outbreak, the simulated results often do not follow a normal distribution. Therefore, the z-score procedure might not be suitable for standardizing the measurement from epidemiologic models. Furthermore, the interpretation of the z-score might not be straightforward. In Table 2.1, the outbreak duration for the depopulation was shortest at 52 days among FMD-control strategies but the z-score of the depopulation was negative (-0.88) and therefore preferable to any FMD-control strategies with a score greater than -0.88. Decision makers might be confused when comparing the effectiveness of FMD-control strategies because the z-scores for depopulation and movement restriction are negative and the z-score for vaccination is positive.

2.5.2. **Zero to one scoring procedure**

The zero to one scoring procedure standardizes the measurement using a maximum and minimum measurement (Hwang and Yoon, 1981).

$$x'_i = (x_i^{max} - x_i)/(x_i{}^{max} - x_i^{min}) \quad \text{(Equation 2.2)}$$

Where x'_i : standardized score of alternative for the *i*th indicator, x_i^{max} : maximum measurement of alternative for the *i*th indicator, x_i : measurement of alternative for the *i*th indicator, and x_i^{min}: minimum measurement of alternative for the *i*th indicator.

After standardization, the scores for each indicator range from zero to one. The higher the standardized score, the larger the impact of the alternative on the result. The alternative with the lowest measurement is always calculated as zero. In other words, the impact of the alternative with the least measurement can be ignored. Therefore, it is a straightforward process to rank the strategy from highest to lowest (1 to 0) and compare the impact of alternatives.

Mourtis et al. (2010) used the zero to one scoring procedure to standardize the measurement of indicators related to CSF-control strategies, such as the duration of CSF outbreak, the number of CSF-infected farms, or the economic loss due to a CSF outbreak. They evaluated the effectiveness of CSF-control strategies by comparing the standardized measurements of different CSF-control strategies. The sums of standardised scores across the indicators were 10.3 for slaughtering CSF-infected farms, 1.3 for pre-emptive slaughtering CSF-susceptible farms within a predefined radius around a CSF-infected farm, and 7.6 for vaccinating CSF-susceptible farms. Therefore, slaughtering CSF-infected farms was a more efficient CSF-control strategy than pre-emptive slaughtering or vaccination.

2.5.3. **Maximum score procedure**

The maximum score procedure standardizes the measurement by dividing each value by the maximum for that indicator (Hwang and Yoon, 1981).

$x'_i = x_i \ / \ x_i^{max}$ (Equation 2.3)

Where x'_i : standardized score of alternative for the *i*th indicator; x_i : measurement of alternative for the *i*th indicator, and x_i^{max} : maximum measurement of alternative for the *i*th indicator.

Like the zero to one scoring procedure, the highest standardized score is calculated as one and the higher the standardized score, the larger the impact on the result. However, unlike the zero to one scoring procedure, for each indicator the least preferred can be determined by identifying the alternative with the lowest measurement. One factor to be aware of when using the maximum score procedure when considering disease control strategies is that there will be times when the ‘worst’ control strategy for an indicator is given a standardized score of zero and the ‘best’ is given the standardized score of one. For example, in Table 2.1 the strategy with the largest number of infected farms, the largest area of disease outbreak area, or the longest duration of disease outbreak is zero. The solution to this problem is simply to transform the score by subtracting the value from one.

To date there are no published studies in the veterinary literature in which the maximum score procedure has been used. However, the maximum score procedure has been used in environmental studies. In Turkey, Ozturk and Batuk (2011) applied the maximum score procedure to standardize the measurement of indicators of flooding, such as runoff, elevation, slope, or drainage density. The standardized score of each indicator was merged with the weight of the indicator to rank the area under five categories: very high (0.85–0.79), high (0.75–0.71), medium (0.71–0.65), low (0.65–0.59) and very low (0.59–0.41). Approximately 95% of flood-affected areas during the years 1970–1997 corresponded to an area labelled with very high or high flood vulnerability.

2.5.4. **Hypothetical example of standardization**

An example of the three standardization procedures is given in Table 2.1. The hypothetical measurements of epidemiologic indicators, such as the duration of disease outbreak and the number of infected farms for depopulation, standstill, and vaccination are shown. Clearly, the scale for each of the measurements is different, and if they are to be combined into a single score it will be necessary to standardize the units. After standardization, the measurements have a common scale. Then, the effectiveness of FMD-control strategies is evaluated by comparing the standardized score of FMD-control strategies.

Table 2.1. A numerical example showing the hypothetical measurement of duration of outbreak and z-score for foot-and-mouth disease (FMD) control strategies

Indicator for epidemiologic criterion	FMD-control strategies		
	Depopulation	Movement standstill	Vaccination
Duration of outbreak in days[a]	52	65	90
Z-score	-0.88	-0.21	1.09
Zero to one score	1.00	0.66	0.00
Maximum score	0.58	0.72	1.00
Number of infected farms[b]	342	457	842
Z-score	-0.78	-0.34	1.13
Zero to one score	1.00	0.77	0.00
Maximum score	0.41	0.54	1.00

[a] mean duration across the three control strategies is 69 days and the standard deviation is 19.3 days

[b] mean number of infected farms across the three strategies is 262 and the standard deviation is 547.

2.6. Determining criterion weights

Central to an MCDA is the need to assign a weight to each of the criteria. This weight indicates how much each stakeholder, or group of stakeholders, cares about the criterion (Gregory et al., 2012). A questionnaire can be used to measure the weight stakeholders assign to each indicator of a criterion. One way to do this is that stakeholders quantify the relative importance of the indicators using numerical values such as scores. Mourtis et al. (2010) surveyed the preferences of the 20 CVOs from the EU about CSF-control strategies using a questionnaire. The questionnaire included 21 indicators, which CVOs judged using a scale from zero to 100. According to their survey, the duration of the CSF outbreak was considered as the most important indicator, with a weight of 30. The weights of other indicators were 29 for the efficacy of CSF-control strategy, 26 for the number of CSF-infected farms, and 21 for the consequential losses affecting the region and the size of affected region.

The limitation of assigning numerical scores is that there may be uncertainty in the weights. The weight of an indicator is commonly determined according to stakeholder’s experience or knowledge. Thus, different stakeholders have different preferences, resulting in a large range of weight values for the indicators. Nevertheless, the use of a numerical unit to quantify the weight is central to the MCDA process and allows a transparent process to be applied to decisions around selection of control strategies for transboundary disease. An alternative to assigning numerical values is to use rankings to measure the relative importance of indicators. The ranks can then be converted to numeric values using methods such as probabilistic inversion (Neslo and Cooke, 2011), as was done by Brookes et al. (2014a) when they prioritised pig diseases in Australia. In that study 430 pig producers were asked which indicators were important when they prioritised pig diseases. Pig producers considered the attack rate of disease as the most important. The order of other indicators, from most to least important, was the length of diseases, the incidence rate in humans, the market loss due to the diseases, and the case-fatality rate. Rankings given to the indicators were converted to a probability distribution based on the assumption that each pig producer has his/her own vectors of rankings on the indicators and hence the population of pig producers has a distribution over possible values for the vectors. The disadvantage of probabilistic inversion is the possibility for uncertainty when estimating the probability distribution. When the rankings of the indicators differ between stakeholders, the probability distributions of rankings may have a large range. Despite the disadvantage of the ranking system for the indicators, it is useful in MCDA for disease control strategies since stakeholders can judge the relative importance of indicators more easily than if they assign numeric values.

Another approach to converting ranks to a numeric value is a fuzzy recognition model. A fuzzy recognition model shows the weight of an indicator in a granulated form instead of a quantified measurement. Stakeholders can assign a relative importance to the indicators using a linguistic value such as severe, normal, or better. As with the rankings of the indicators, the frequency of granulated forms is transformed to a numerical unit to assign a value to the indicators (see Chen et al. (2004) for mathematical details of this technique). The fuzzy recognition technique is complex and there are no examples of its use in veterinary science decision making.

2.7. Calculating overall scores and rankings

After determining a value for the indicators and the weight to apply to each indicator by stakeholders, the next step is to calculate the overall score for each of the alternatives. The preferred alternative is the one with the highest overall score among the alternatives. In MCDA, there are three methods of combining the scores of the indicators with the weights to generate the overall score: 1) Value measurement model, 2) Reference level model, and 3) Outranking model (Mendoza and Martins, 2006).

2.7.1. **Value measurement model**

The value measurement model calculates the overall score of each alternative as the sum of standardized scores taking into account the weight of the indicators as shown in Equation 2.4 (Mendoza and Martins, 2006).

$$S_j = \sum_{i=1}^{n} x'_i \times W_i \quad \text{(Equation 2.4)}$$

Where S_j : the score of alternative j; x'_i : standardized score of alternative for the *i*th indicator; and W_i : weight for the *i*th indicator.

There are two underlying assumptions in the value measurement approach to aggregating indicators: first, the indicators are preferentially independent, and second, the measurements of the indicators are on the same scale (Stewart, 2014). If the measurement of one indicator does not depend on the level of the measurement of the other indicator, the indicator is said to be preferentially independent. The performance of the alternatives for the indicators should be measured using the same scale to compare the performance to each alternative and to calculate the overall scores of alternatives.

The value measurement model is suitable for ranking alternatives since the alternatives can be ordered according to their overall scores. Mourtis et al. (2010) applied the value measurement model to rank CSF-control strategies with the perspectives of 20 CVOs from the Europe. The CSF-control strategies were scored using epidemiologic, economic, and ethical indicators and then the scores were multiplied by the weights of the indicators, which were obtained from the CVOs. As a result, slaughtering only the CSF-infected pigs was the highest scored strategy, followed by slaughtering CSF-susceptible pigs near CSF-infected farms, vaccinating and slaughtering CSF-susceptible pigs near CSF-infected farms, and vaccinating CSF-susceptible pigs near CSF-infected farms. However, the assumption of preferential independence was violated in the study because epidemiologic, economic, and ethical indicators were mutually associated with each other. Brookes et al. (2014a) used the value measurement model to calculate the overall importance of the exotic diseases for the pig industry in Australia. Exotic pig diseases, such as FMD, CSF, or Aujeszky’s disease, were scored using indicators such as pork market loss, attack rate for pigs on a single farm, length of the disease, and incidence in humans, and then the scores were multiplied by weights. As a result, FMD was considered the most important disease among the exotic diseases for the Australian pig industry.

2.7.2. **Reference level model**

The reference level model evaluates the proximity of alternatives to a predetermined level of achievement for an indicator; in other words, a reference level (Laken, 2007). If the measurement of the alternative cannot achieve a satisfactory level for the indicator, then the measurement is ruled out in the evaluation for the indicator as shown in Equation 2.5.

$A_j = \sum_{i=1}^{n}((x_i | x_i \geq \ R_i))$ (Equation 2.5)

Where A_j : the attribute value of alternative j; x_i : transformed standardized score of alternative for the ith indicator; and R_i : reference level for the ith indicator.

Generally, control strategies for transboundary livestock diseases have to satisfy a minimum acceptable level of performance (i.e. reference level) to be considered a preferable strategy. Control strategies falling below the reference level will be rejected because the performance of the other indicators cannot compensate for this deficiency. For example, if the duration of an FMD outbreak for a vaccination control alternative exceeds the pre-defined period, vaccination is rejected at the beginning of MCDA.

There are fewer examples of reference level models for control strategies because the reference levels of the indicators often need to be subjective and require consideration of the views of many stakeholders. For example, the reference level assigned to the number of depopulated farms may differ between CVOs, farmers, and members of the general public. The difference between preference levels can be explored using a sensitivity analysis. While the approach measures the impact of the reference level on the results, it does not actually help determine what reference level should be selected.

2.7.3. **Outranking model**

The outranking model is used to compare alternatives in a pair-wise manner in relation to indicators, and asserts the preference of one alternative over another for the indicators (Laken, 2007; Behzadian et al., 2010). In practice, it is rare that one strategy performs better than another strategy across all indicators. Outranking models aggregate the preference information across all indicators to provide evidence for selecting one alternative over another (Hajkowicz and Collins, 2007). To date there are no published studies in the veterinary literature in which the outranking model has been used. However, the outranking model has been used in environmental studies. In Turkey, Ozkan (2013) used an outranking model to evaluate five healthcare waste treatment methods: incineration, microwaving, on-site sterilization, off-site sterilization, and landfill. Each intervention was evaluated with respect to its effectiveness for nine indicators: waste volume reduction, microbial inactivation, energy recovery, capital cost, operating cost, greenhouse gas emissions that affect people's health, solid residuals, and hygiene. The overall scores of interventions were then compared in a pair-wise manner, showing that an off-site sterilization was dominant over all the other healthcare waste treatment methods.

2.7.4. **Hypothetical example of calculating overall score**

An example of the calculation procedures of overall scores for FMD-control strategies is given in Table 2.2. For the value measurement model, the FMD-control strategies with the highest weighted scores were depopulation for the epidemiologic criterion, movement standstill for the economic criterion, vaccination for the social-environmental criterion, and movement standstill overall. For the reference level model, the measurements of economic and social indicators for depopulation were excluded in the attribute value because those were below the reference level. Likewise, the epidemiologic and social indicator measurements for standstill and the epidemiologic and economic indicator measurements for vaccination were excluded. Overall, movement standstill was the most preferred FMD-control strategy. For the outranking model, movement standstill performed better than depopulation and vaccination. Thus, a decision maker can conclude that movement standstill would be better than the other FMD-control strategies.

Table 2.2. A numerical example showing the hypothetical calculation of overall scores for three foot-and-mouth disease (FMD) control strategies: depopulation, movement standstill, and vaccination.

Criteria	Score	FMD-control strategies		
		Depopulation	Movement standstill	Vaccination
Epidemiologic	Standardised Score	30	25	20
	Weight	0.8	0.8	0.8
	Weighted score	24	20	16

	Reference value	22	22	22
Economic	Standardised Score	15	25	20
	Weight	0.6	0.6	0.6
	Weighted score	9	15	12
	Reference value	15	15	15
Social-environmental	Standardised Score	10	20	30
	Weight	0.5	0.5	0.5
	Weighted score	5	10	15
	Reference value	10	10	10
Overall score	Value measurement model	38	45	43
	Reference level model	24	25	15
	Outranking model*	-12	9	3

* The overall score of the outranking model was the sum of the difference in the overall scores of FMD-control strategies with each other.

2.8. Sensitivity analysis

Uncertainties make reliable and transparent decision making processes difficult to achieve (Dijkhuizen et al., 1994). The quality of a decision would be decreased when uncertainty exists because decision quality is assessed by how the decision is made rather than the actual result (Ge et al., 2007). Within an MCDA framework there can be uncertainty in the values assigned to indicators and the weighting assigned to the indicators. In addition, the results could be influenced by the methods used to standardise values as well as those used to combine indicators to determine scores. Within an MCDA framework it is essential that a sensitivity analysis is conducted to explore the uncertainty and its impact on decision making.

When considering transboundary livestock diseases, the values assigned to indicators under different alternatives are typically derived from a simulation of a disease outbreak. The problem with the application of models is that a disease outbreak is complex, with a reaction of many stochastic processes which cannot be directly detectable (Kitching et al., 2005). It is not feasible to quantify the probability of every disease transmission route. In addition, the probability of infection depends on several factors, such as environmental conditions or the immunity level of susceptible animals. The incubation period of the disease might be different under different environmental conditions, resulting in a range of infection probabilities for susceptible animals. Practically, it might not be possible to quantify all variables of disease spread, so there would be an uncertainty in the information related to the disease outbreak.

Sensitivity analysis starts with the identification of variables with uncertainty. If the input value of variables is assumed, because no information is available, the impacts of the variables on the results are evaluated. Sensitivity analysis is performed by changing the input values of variables with uncertainty and comparing the results with those assuming default input values (Owen et al., 2011). If the differences between the results under different input values are rather small, the uncertainty of the measurement may not be influential on the final decision. The degree of uncertainty of the variables would be described using a distribution function. To quantify the degree of uncertainty, a simulation method, such as the Latin hypercube simulation, can be used.

In MCDA, the weights of the indicators may be uncertain because no information is available or stakeholders have different preferences for the indicators. Sensitivity analysis is used to measure the impact of the weight on the results. To measure the impact of the weight on the results of decision analysis, Butler et al. (1997) proposed three methods: random weight, rank order weight, and response distribution weight. As the name implies, random weight generates the weight randomly. Rank order weight also generates values randomly but it preserves the rank order of the indicators. Response distribution weight generates values randomly taking into account the interval weights between indicators. The result of decision analysis (i.e. the rankings of alternatives) with the default weight is compared with the results with the generated weight. If the order of rankings does not differ, the uncertainty in the weight has little impact on the final decision making.

2.9. Conclusion

Historically, selection of the best control strategy has focused almost entirely on the epidemiologic criterion. In recent times there has been an increase in the consideration of economic factors but this is often done without considering trade-offs around epidemiologic effectiveness. Unfortunately, there has been no explicated consideration of social and environmental factors for transboundary diseases. This thesis will demonstrate the utility of MCDA in combining epidemiologic, economic, and social indicators in the post-hoc evaluation of FMD-control strategies. While MCDA has been used for some time in environmental science, there are a limited number of applications of MCDA in the veterinary literature (Ge et al., 2007; Cox et al., 2013; Brookes et al., 2014a; Brookes et al., 2014b) and only one focused on the evaluation of control strategies (Mourits et al., 2010). Furthermore, in this example the epidemiologic and economic criteria were not specifically assessed. This thesis will describe how to measure the epidemiologic, economic, and social-environmental effectiveness of FMD-control strategies and will provide a framework to aggregate these measurements from the perspectives of CVOs.

To demonstrate the utility of MCDA, FMD is selected as an example of a transboundary livestock disease, and FMD-control strategies will be evaluated to choose the best FMD-control strategy from the perspectives of CVOs. To do this, we will use data from the 2010/11 FMD outbreak in the city of Andong, Republic of Korea, and the preferences of 21 representatives of CVOs from the Asia-Oceania region.

The objectives of the thesis are to:

1. Measure the preferences of CVOs for control of an FMD outbreak using a questionnaire study for determining the weights of the indicators for each criterion for MCDA to evaluate FMD-control strategies (Chapter 3);
2. Evaluate the epidemiologic effectiveness of FMD-control strategies using a simulation model for measuring the epidemiologic criterion for MCDA to evaluate FMD-control strategies (Chapter 4);
3. Evaluate the economic effectiveness of FMD-control strategies using a cost-effectiveness analysis for measuring the economic criterion for MCDA to evaluate FMD-control strategies (Chapter 5);
4. Evaluate the effectiveness of FMD-control strategies using an MCDA with three criteria: epidemiologic, economic, and social-environmental, based on the results from Chapters 3, 4 and 5 (Chapter 6).

Chapter III

3 Criteria and indicators for foot-and-mouth disease (FMD) control strategy decision making in Asia-Oceania countries

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Abstract

The objective of this study was to identify the relative importance of criteria that could be used to evaluate control strategies for foot-and-mouth disease (FMD). A questionnaire was distributed to 21 chief veterinary officers (CVOs) or their representatives during the 28th Conference of the Regional Commission for Asia, the Far East and Oceania of the World Organisation for Animal Health (OIE). All representatives completed the questionnaire, which evaluated the importance of epidemiologic, economic, and social-environmental criteria in the FMD control decision-making process. In the epidemiologic criterion, size of an FMD outbreak area was the most important indicator from the perspective of the CVOs. The direct cost of an FMD-control strategy was considered the most important indicator in the economic criterion. In the social-environmental criterion, mental health of FMD-affected farmers was the most important indicator. With respect to the FMD status of a country, the economic criterion was considered more important in FMD-free countries than in countries that had experienced FMD. The current survey of the relative importance of criteria would facilitate a clear and transparent discussion around the implications of FMD-control strategy and a rapid response during an FMD outbreak.

3.1 Introduction

Foot-and-mouth disease (FMD) epidemics have economic, environmental, and social impacts. The 2001 FMD epidemic in the United Kingdom (UK) resulted in a loss to the UK's agriculture industry of approximately GBP 3.1 billion (Thompson et al., 2002). Most economic losses were compensation for slaughtered animals and costs associated with the disposal of carcasses. The method of carcass disposal, such as burning or burying, could also have a damaging effect on the environment

(McDaniel, 1991). In addition, when considering control options for FMD, ethical issues, including animal welfare, must be considered because some people consider mass culling of animals or burning carcasses to be cruel (Murphy-Lawless, 2004). Therefore, it is potentially important for decision makers to consider epidemiologic, economic, environmental, and social issues when selecting an appropriate FMD-control strategy. Furthermore, if key stakeholders are involved in setting criteria and relative importance this could speed up the implementation of control measures and thereby increase their effectiveness (Hueston, 2007).

A decision support tool that could help reach a decision is a Multi-criteria decision analysis (MCDA), which considers stakeholders' preferences in the decision making process. MCDA consists of three steps: formulating the problem, evaluating possible solutions, and balancing stakeholders' preferences (Gregory et al., 2012). The problem is defined and the stakeholders identified, then a process to evaluate possible options for solving the problem is followed. Finally, the choice of solution is explained and justified.

Only one research paper has used MCDA to describe preferences for the control of an animal disease; this was for classical swine fever in Europe (Mourits et al., 2010). To date, MCDA has not been used to evaluate FMD-control options nor has the technique been applied to animal health problems in countries in the Asia/Oceania region where FMD is absent from some countries but endemic in others. Moreover, nothing has been reported about what representatives of the veterinary offices in Asia and Oceania consider important in choosing an FMD-control strategy. This paper describes results of a survey of chief veterinary officers (CVOs) or their representatives to determine the relative importance of indicators in choosing an FMD-control strategy.

3.2 Materials and methods

3.2.1 Stakeholders and questionnaire

The study participants were 21 CVOs, or their representatives, from countries in the Asia-Oceania Region who attended the 28th Regional Commission for Asia, the Far East and Oceania of the World Organisation for Animal Health (OIE). Participants completed the survey and responses were collected on 19 November 2013 (OIE, 2013a). The questionnaire comprised 42 questions: 21 rank and 21 score questions. The rank questions indicated the priority of indicators used when making a decision about an FMD-control strategy. The rank ranged from 1 to 6, where 1 was the highest priority indicator and 6 the least. The score questions quantified the relative importance of indicators in the FMD-control strategy. Possible scores ranged from 0 to 100 with higher scores being more important. Each question was related to the preference of stakeholders according to three criteria: epidemiologic, economic, and social-environmental. Questions about the epidemiologic criterion addressed the importance of epidemiologic effectiveness of FMD-control strategies, including duration of the epidemic, the size of outbreak area, and the number of infected farms and animals. Questions about the economic results of FMD-control strategies addressed indicators like the management cost of FMD-control, the loss from depopulated farms and animals, and the decrease in animal products exported. The social-environmental component contained questions about the effects of FMD epidemics on human and environmental health; for example, questions related to the mental health of the public or of farmers with FMD-affected farms, the effects of carcass disposal on the environment, or animal/human welfare.

A binary variable was created to code the FMD status of each of the 21 countries. A country was considered as FMD-free if an FMD outbreak had not been reported to the OIE in the ten years prior to the survey and FMD-experienced if there had been an FMD outbreak within the same period (http://www.oie.int/wahis_2/public/wahid.php/Wahidhome/Home). The classification system used in this paper is not the same as that used by the OIE when determining country status. Specifically, in the current study some countries classified as ‘FMD-experienced’ may have eradicated FMD either with or without vaccination and would be considered as FMD-free by OIE; however, if this country had FMD reported in the last 10 years then it was considered as FMD-experienced in this paper (Table 3.1).

3.2.2 Data analysis

Results from the questionnaire were entered into Microsoft Excel (Microsoft Corporation, Washington, United States) and analysed with R, version 3.1.0 (R Core Team, Vienna, Austria). Statistical analyses consisted of two parts, descriptive and inferential. The relative importance of each of the six indicators in each of the three criteria was expressed using the minimum, median and maximum score. The differences of the relative importance between FMD-experienced countries and FMD-free countries were explored using the Mann-Whitney-Wilcoxon test and significance was indicated by $p<0.05$. The rank of criteria and indicators was only used to confirm the score was given in an appropriate manner; in other words, higher ranked criteria or indicators should have higher scores.

3.3 Results

All 21 CVOs or their representatives at the meeting completed the questionnaire and there were no missing values. Among 21 CVOs or their representatives, 12 were from FMD-experienced countries and nine from FMD-free countries. When determining an FMD-control strategy, the epidemiologic criterion was preferred, with a median relative importance score of 90 (range 50–100; Table 3.2). Median relative importance scores for the economic and social-environmental criteria were 85 (range 40–100) and 80 (range 25–98), respectively.

With respect to FMD status, only the economic criterion showed a statistically significant difference in relative importance between FMD-experienced and FMD-free countries; these were 80 (range 50–95) and 95 (range 40–100), respectively. The median scores of epidemiologic, economic, and social-environmental criteria for the FMD-free countries were higher compared with those from the FMD-experienced countries. In addition, the ranges of the scores were larger in the FMD-free than the FMD-experienced countries. The range of epidemiologic scores was 20 (range 80–100) in FMD-experienced countries and 50 (range 50–100) in FMD-free countries. The range of economic scores for FMD-experienced countries was 45 (50–95) and for FMD-free countries was 60 (40–100). The range of social-environmental scores was 55 (25–80) for FMD-experienced countries and 68 (30–98) for FMD-free countries.

The relative importance scores of each indicator in three criteria: epidemiologic, economic, and social-environmental, are shown in Tables 3.3–3.5. In the epidemiologic criterion, size of FMD outbreak area was regarded as the most important indicator, with a median relative importance score of 90 (range 45–100; Table 3.3). The other indicators in the epidemiologic criterion, in decreasing order of importance, were duration of FMD epidemics, number of infected farms, number of infected animals, number of depopulated farms, and number of depopulated animals. There were no statistically significant differences among relative importance scores for each indicator between FMD-experienced and FMD-free countries. The order of importance for indicators in the epidemiologic criterion was similar for FMD-experienced and FMD-free countries. Both types of countries considered the size of FMD outbreak area the most important among 6 indicators. The median relative importance scores of the FMD outbreak area were 90 (range 50–100) in FMD-experienced countries and 88 (range 45–98), in FMD-free countries. However, median relative importance scores associated with depopulation in FMD-experienced countries were approximately half those in FMD-free countries. The median score of the number of depopulated farms was 30 (range 5–80) in FMD-experienced countries but 60 (range 10–80) in FMD-free countries, while the median score of the number of depopulated animals was 20 (range 5–95) in FMD-experienced countries but was 43 (range 5–85) in FMD-free countries.

In the economic criterion, cost of control measures was considered the overall most important indicator, with a median relative importance score of 80 (range 30–100; Table 3.4). The other indicators, in decreasing order of importance, were farm loss from depopulation, farm loss from movement restriction, industry loss from movement restriction, export loss, and tourism loss. As with the epidemiologic criterion, there was no statistically significant difference in indicator scores between FMD-experienced and FMD-free countries.

In the social-environmental criterion, mental health of farmers with farms affected by FMD was considered the most important indicator, with a median score of 70 (range 5–100; Table 3.5). The other indicators, in decreasing order of importance, were mental health of the public, welfare of FMD-infected animals, welfare of non-infected animals, air pollution, and ground pollution due to carcass disposal. Highest scored indicators differed according to FMD status. FMD-experienced countries had a median score of 80 (range 40–100) for the mental health indicator, whereas FMD-free countries had a median score of 73 (range 0–100) for ground pollution due to carcass disposal. FMD-free countries gave higher scores to environmental indicators such as air pollution and ground pollution than did FMD-experienced countries. For example, the median score of air pollution in FMD-free countries was 67 (range 5–90) but in FMD-experienced countries it was 10 (range 5–90).

3.4 Discussion

This survey of 21 CVOs or their representatives from the Asia-Oceania Region is the first published study to evaluate the preference of indicators used in making a decision regarding FMD-control strategies. The study found that the epidemiologic criterion was the most important criterion when deciding between control strategies. In other words, when representatives chose an FMD-control strategy, epidemiologic indicators such as duration of FMD epidemics, size of FMD outbreak area, or number of FMD impacted farms were more important than indicators used to determine the financial or social-environmental criteria. For classical swine fever (CSF), Mourtis et al. (2011) reported the same criteria ranking as we found in this study. The stakeholders in Mourtis' study and ours were CVOs or their representatives in Europe and the Asia-Oceania region, respectively. While the epidemiologic criterion was preferred by these respondents, it may not be preferred by another decision maker, who may have an economic focus. For example, farmers will consider economic indicators such as the financial loss from an FMD outbreak to be more important than epidemiologic indicators such as the duration of the outbreak.

The study found that while the ranking of median relative importance of the epidemiologic and social-environmental criteria was not statistically significantly different between CVOs from countries considered FMD-free and not, the relative importance of economic indicators was. The economic loss from the FMD epidemic and the economic effectiveness of the FMD-control strategy were considered more important for the FMD-control decision making process in FMD-free countries than in FMD-experienced countries. Some FMD-free countries in the Asia-Oceania region, such as Australia or New Zealand, are major animal product exporting countries; therefore those countries gave high scores on the economic indicators. However, FMD-experienced countries such as the Republic of Korea or Cambodia, where exporting animal products is less important, had relatively lower scores than FMD-free countries.

No statistically significant difference was found in the median relative importance scores of indicators between FMD-experienced and FMD-free countries. Nevertheless, FMD status of a country is an important factor for understanding the background of decision making for an FMD-control strategy. For instance, representatives from FMD-experienced countries gave lower scores on the epidemiologic indicator ‘number of depopulated farms’ than representatives from FMD-free countries. This indicates that pre-emptive slaughtering, which can result in a large number of depopulated farms, would be preferred more for controlling FMD spread in an FMD-experienced country than in an FMD-free country.

In the study, the CVOs or their representatives in the Asia-Oceania region scored their preferences for six indicators in each criterion. In the epidemiologic criterion, size of FMD outbreak area was the most important indicator followed by the duration of the FMD epidemic. In contrast, CVOs in the European Union (EU) considered the duration of epidemics more important than the size of outbreak area when considering CSF-control strategies (Mourits et al., 2010). Furthermore, the order of epidemiologic indicators differed between the current study and the EU study, which ranked, in decreasing order, duration of epidemics, number of infected farms, size of outbreak area, number of depopulated farms, and number of depopulated animals. This difference could be interpreted as being associated with either the different region or different disease.

A difference in the relative importance of indicators was also found in the economic criterion between this and the EU study. The cost of organising a control strategy, such as labour and equipment costs for control measures, was ranked number one in the present study but number five in the EU study. This indicates that CVOs in the Asia-Oceania region and the EU had different economic and epidemiologic perspectives for choosing a disease control strategy.

For the social-environmental criterion, the EU study and the current study could not be compared because different criteria and indicators were used. In the EU study, a social-ethical criterion was applied instead of the social-environmental one; for example, the EU study evaluated efficacy of CSF-control strategies, social-economic impact, macro-economic impact, impact related commerce, animal health, and animal welfare. Among indicators, EU CVOs considered the efficacy of CSF-control strategies the most important. However, in the current study, the efficacy of FMD-control strategies was evaluated in the epidemiologic criterion and no efficacy indicators were included in the social-environmental criterion. Therefore, the difference in CVOs' preference between EU and Asia-Oceania for a social criterion has not been reported here.

The small sample size of the study — 21 representatives of 31 OIE member countries in the Asia-Oceania region — may have small power and may not truly represent the preference of CVOs in the study region. Countries from the region but not included in the study because they were not at the meeting were Bangladesh, Bhutan, India, Korea (Dep. of), Laos, Maldives, Nepal, Pakistan, Timor Leste, and Vanuatu. While results and conclusions apply only to the study region, the survey process can be applied to evaluate the CVOs' preferences for FMD-control strategies in other regions, such as Europe or the Americas.

There is some probability of interaction between the indicators included in the study. Indicators were categorized into three criteria; epidemiologic, economic, and social-environmental, with six indicators in each criterion. However, each economic and social-environmental indicator was related to an epidemiologic indicator. For example, a long duration of an FMD epidemic can also result in a severe financial loss to the livestock industry and farms. A larger outbreak in terms of animal numbers will also result in more animals slaughtered and greater environmental contamination. Nevertheless, we wanted to include all three criteria when collecting the preferences because previous evaluations of the success of transboundary livestock disease control strategies were based on these three criteria (Mourits et al., 2010; Brosig et al., 2013). The probability of interaction could be verified and quantified by asking individual CVOs whether the preference scores were assigned independently. However, this verification was not processed in the study because of the limited availability of CVOs. Therefore, a further survey of preference based on the current study would be improved if the interactions between criteria were to be verified.

3.5 Conclusion

This represents one of the first attempts to have CVOs describe the relative importance of criteria for evaluating potential control strategies for FMD and exploring whether preferences are affected by disease status. Interestingly, the study found that the epidemiologic indicators, in particular the size of the FMD-infected area, were considered most important for choosing an FMD-control strategy. The importance of the economic criterion differed with FMD status of a country; specifically, those countries considered free of FMD ranked economic indicators as more important than those without FMD. Regardless of FMD status the environmental and social indicators were considered the least important. The approach could easily be applied to CVOs’ preferences for FMD-control strategies in other regions, such as Europe or the Americas. While CVOs should accept much of the responsibility for decision making during an outbreak their decisions are not made in a vacuum. Therefore, there could be merit in undertaking a process like this to specifically collect the views of different stakeholders. Such information would facilitate a clear and transparent discussion around trade-offs and implications, which should improve the willingness for different sectors to engage in preparatory responses prior to an outbreak, and also to respond rapidly during an outbreak.

Table 3.1. Foot-and-mouth disease (FMD) status of 21 participant countries in the study.

Country	FMD Free? [a]
Australia	Yes
Brunei Darussalam	Yes
Cambodia	No
China (People's Republic of)	No
Chinese Taipei	No
Fiji	Yes
Indonesia	Yes
Iraq	No
Japan	No
Korea (Republic of)	No
Malaysia	No
Mongolia	No
New Caledonia	Yes
New Zealand	Yes
Papua New Guinea	Yes
Philippines	Yes
Russia	No
Singapore	Yes
Sri Lanka	No
Thailand	No
Vietnam	No

[a] A country was considered free of FMD if there had been no outbreaks within last 10 years.

Table 3.2. The relative importance scores of criteria for a foot-and-mouth disease (FMD) control strategy according to the preferences of 21 chief veterinary officers (CVOs) or their representatives from the Asia-Oceania region.

Criterion	FMD Free[a]	Rank	Minimum	Median	Maximum	p-value
Epidemiologic	No	1	80	90	100	0.26
	Yes	1	50	95	100	
	Overall	1	50	90	100	
Economic	No	2	50	80	95	0.04
	Yes	2	40	95	100	
	Overall	2	40	85	100	
Social -environmental	No	3	25	61	80	0.13
	Yes	3	30	80	98	
	Overall	3	25	80	98	

[a] Data were grouped by the FMD status of country. A country was considered free if there was no FMD outbreak in the last 10 years (FMD-free, n = 9) and classified as not free of FMD if there had been an FMD outbreak within last 10 years (FMD-experienced, n=12).

Table 3.3. The relative importance scores of indicators in the epidemiologic criterion for a foot-and-mouth disease (FMD) control strategy according to the preferences of 21 chief veterinary officers (CVOs) or their representatives from the Asia-Oceania region.

Indicator	FMD Free[a]	Minimum	Median	Maximum	p-value
Duration of FMD	No	10	70	95	0.53
	Yes	10	84	100	
	Overall	10	80	100	
Size of FMD outbreak area	No	50	90	100	0.78
	Yes	45	88	98	
	Overall	45	90	100	
No. of infected farms	No	30	80	98	0.78
	Yes	35	73	95	
	Overall	30	78	98	
No. of infected animals	No	30	60	90	0.52
	Yes	20	60	98	
	Overall	20	60	98	
No. of depopulated farms	No	5	30	80	0.15
	Yes	10	60	80	
	Overall	5	40	80	
No. of depopulated animals	No	5	20	95	0.24
	Yes	5	43	85	
	Overall	5	30	95	

[a] Data were grouped by the FMD status of country. A country was considered free from FMD if there was no FMD outbreak in the last 10 years (FMD-free, n = 9) and classified as not free from FMD if there had been an FMD outbreak within last 10 years (FMD-experienced, n=12).

Table 3.4. The relative importance scores of indicators in the economic criterion for a foot-and-mouth disease (FMD) control strategy according to the preferences of 21 chief veterinary officers (CVOs) or their representatives from the Asia-Oceania region.

Indicator	FMD Free[a]	Minimum	Median	Maximum	p-value
Cost of control measures	No	30	83	100	0.47
	Yes	50	75	90	
	Overall	30	80	100	
Farm loss from depopulation	No	5	70	100	0.80
	Yes	30	70	100	
	Overall	5	75	100	
Farm loss from movement restriction	No	50	80	90	0.07
	Yes	5	64	85	
	Overall	5	70	90	
Industry loss from movement restriction	No	30	60	90	0.75
	Yes	30	75	93	
	Overall	30	70	93	
Export loss	No	5	50	95	0.83
	Yes	10	45	100	
	Overall	5	50	100	
Tourism loss	No	5	25	65	0.99
	Yes	5	13	90	
	Overall	5	20	90	

[a] Data were grouped by the FMD status of country. A country was considered free from FMD if there was no FMD outbreak in the last 10 years (FMD-free, n = 9) and classified as not free from FMD if there had been an FMD outbreak within last 10 years (FMD-experienced, n=12).

Table 3.5. The relative importance scores of indicators in the social-environmental criterion for a foot-and-mouth disease (FMD) control strategy according to the preferences of 21 chief veterinary officers (CVOs) or their representatives from the Asia-Oceania region.

Indicator	FMD Free[a]	Minimum	Median	Maximum	p-value
Mental health of affected farmers	No	40	80	100	0.46
	Yes	5	62	100	
	Overall	5	70	100	
Mental health of the public	No	25	70	80	0.55
	Yes	10	53	100	
	Overall	10	60	100	
Welfare of infected animals	No	5	62	100	0.43
	Yes	30	53	80	
	Overall	5	60	100	
Welfare of non-infected animals	No	5	60	85	0.83
	Yes	20	50	90	
	Overall	5	50	90	
Air pollution	No	5	10	90	0.29
	Yes	5	67	90	
	Overall	5	50	90	
Ground pollution	No	5	30	100	0.34
	Yes	0	73	90	
	Overall	0	50	100	

[a] Data were grouped by the FMD status of country. A country was considered free from FMD if there was no FMD outbreak in the last 10 years (FMD-free, n = 9) and classified as not free from FMD if there had been an FMD outbreak within last 10 years (FMD-experienced, n=12).

Chapter IV

4 Simulation modelling to evaluate the effectiveness of control strategies during the 2010/11 foot-and-mouth disease (FMD) epidemic in the city of Andong, Republic of Korea

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Abstract

A simulation model of the 2010/11 foot-and-mouth disease (FMD) epidemic in the city of Andong, Republic of Korea was constructed to evaluate the epidemiologic effectiveness of FMD-control strategies. Seven FMD-control strategies were evaluated with respect to a number of epidemiologic indicators relating to the outbreak, such as number of infected animals, number of infected farms, and epidemic duration. All strategies included pre-emptive slaughtering, movement restriction, and vaccination; however, levels of each control option differed. The constructed simulation model was representative of the 2010/11 FMD epidemic in its prediction of two outcomes: the median number of simulated FMD-detected farms was 270 (range 111–496), which was close to the number of detected farms during the actual FMD epidemic (n=299); and the simulated epidemic curve was similar to the actual epidemic curve of the 2010/11 FMD epidemic. Thus, the constructed model could be used as a reference for evaluating the effectiveness of FMD-control strategies. The effectiveness evaluation of simulated FMD-control strategies emphasized the amount the FMD outbreak size could have increased if the radius of pre-emptive slaughtering area or the duration of movement restriction were decreased. The FMD-control strategy with a five kilometre radius for pre-emptive slaughtering, 100 days of movement restriction, and vaccinating all FMD-susceptible animals in the study area delivered the least number of FMD-infected animals among FMD-control strategies. The FMD simulation model represents a tool for evaluating the effectiveness of FMD-control strategies by comparing the simulated FMD epidemic results for specific areas.

4.1 Introduction

Foot-and-mouth disease (FMD) can spread rapidly to susceptible animals such as cattle, pigs, and deer and can result in a significant economic impact on the livestock industry, directly through lost production (Grubman and Baxt, 2004) and indirectly due to trade restrictions (Thompson et al., 2002). In addition, there are substantial costs associated with the control and eradication of FMD, including culling of infected and at-risk animals, vaccination, and surveillance. To eliminate FMD and reduce the size and costs of an outbreak, the most important priority for decision makers is timely implementation of control strategies (Morris et al., 2002).

According to a previous study (Mourits et al., 2010), chief veterinary officers from Europe who make decisions regarding livestock disease control strategies considered the epidemiologic criterion as more important than the economic or social criterion when evaluating a disease control strategy. However, decision makers often face uncertainties regarding the epidemiologic effectiveness of control strategies. Simulation models are an internationally recognised tool for addressing uncertainty and evaluating the epidemiologic consequences of different FMD-control strategies (Garner and Hamilton, 2011; Willeberg et al., 2011). Model predictions of the size of the outbreak or the epidemic period provide scientific advice regarding the selection of FMD-control strategies. The World Organisation for Animal Health (OIE) conducted a survey of its 168 member countries in 2007 and found that 49% (50) of the 103 respondents were using simulation models in animal disease contingency plans (Sanson et al., 2011; Willeberg et al., 2011). In this survey, 92% (49/53) of respondents who had not used models reported they would like to develop models for disease contingency planning for their countries. Simulation models of FMD-control strategies have been developed to support decision making in Australia (Garner and Beckett, 2005), New Zealand (Sanson et al., 2011; Stevenson et al., 2013), the Republic of Korea (Yoon et al., 2006), the United Kingdom (Morris et al., 2001), and the United States (Bates et al., 2003b; Carpenter et al., 2011). The goal of the present study was to parameterize a simulation model to mimic the 2010/2011 FMD epidemic in the city of Andong, Republic of Korea and then evaluate the effectiveness of alternative FMD-control strategies in terms of FMD-infected animals and farms and the duration of a simulated FMD epidemic. The effectiveness of FMD-control strategies was used to measure the epidemiologic criterion in multi-criteria decision analysis of FMD-control strategies.

4.2 Materials and methods

4.2.1 InterSpread Plus

InterSpread Plus (ISP) is a spatial, state-transition simulation software application that has previously been used to simulate the spread of FMD between farms in the Republic of Korea (Yoon et al., 2006) and the United Kingdom (Morris et al., 2001; Thompson et al., 2002). The model was used here to simulate the spatial and temporal spread of FMD by categorizing which farms in the at-risk population were likely to be infected each day of the outbreak per FMD-control strategy. Simulation outcomes were the number of farms and animals that were infected, detected, slaughtered, or vaccinated during the simulated FMD epidemic, and the duration of the FMD epidemic.

4.2.2 Study population

The study area was the city of Andong, Republic of Korea, the index city of the 2010/11 FMD epidemic. Andong covers approximately 120 square kilometres. When registered in October 2010, the FMD-susceptible population in the city consisted of 2364 Korean beef cow farms, six dairy cow farms, 87 pig farms, five sheep farms, and two deer farms (MOSPA, 2011). Of the 2364 Korean beef cow farms, 880 farms were small holdings (<4 cows) and 79 were intensive commercial scale farms (>100 cows). Three of the six dairy farms had over 100 dairy cows. The average farm size was 20 for beef and 1167 for pigs. Sheep and deer farms were excluded from modelling because there was no applicable information about the farms and no FMD-infection was confirmed in those farms during the 2010/11 FMD epidemic. Farm information, including a unique identification number, point coordinates, farm type, and the number of animals on the farm, was collected from the Korean National Statistics (KOSTAT, 2013).

4.2.3 Epidemic history

During the 2010/11 FMD epidemic in the study area, 281 beef and 17 pig farms were confirmed with FMD infection (MOSPA, 2011). The epidemic duration was 58 days, from 11 November 2010 to 6 January 2011 (Figure 4.1). An animal with clinical signs of FMD was reported on 23 November (day 1) and the farm was confirmed with FMD-infection on 29 November (day 7) (Yoon et al., 2013).

FMD-control measures, such as active surveillance, movement restriction, pre-emptive slaughtering, and vaccination, were applied on 30 November (day 8) for active surveillance and movement restriction, 2 December (day 10) for pre-emptive slaughtering, and 25 December (day 32) for vaccination (MOSPA, 2011). All FMD-control strategies were continued until the end of the FMD epidemic in the study area. 1236 beef and 66 pig farms were depopulated. In addition, vaccination was applied to all FMD-susceptible farms in the study area where animals were not depopulated. In the model, five pig farms were selected as disease starting points (index cases) for simulated FMD spread to replicate what was reported during the 2010/11 epidemic (Yoon et al., 2013). One pig farm was set as FMD-infected on the first day of simulation and two pig farms were set as FMD-infected on the second and third day of simulation, respectively (Figure 4.2). Data reporting the number of affected animals were not available for this study.

4.2.4 Simulation of infectivity and mode of transmission

Transmission of FMD is based on the infectivity of FMD virus and mode of transmission between FMD-infectious and FMD-susceptible animals. The infectivity of FMD virus is the capability of the virus to transmit from FMD-infectious animals to FMD-susceptible animals. Animal species and incubation and infectious periods of the FMD virus are serotype dependent. In this study, FMD virus serotype O, which was confirmed during the 2010/11 FMD epidemic, was used to simulate the infectivity of FMD virus (Yoon et al., 2013). The mode of transmission is the route by which the FMD virus is transmitted from FMD-infectious animals to FMD-susceptible animals. The FMD virus can spread through direct contact, indirect contact, local area spread, or airborne spread (Davies, 2002).

4.2.4.1 Infectivity of FMD virus

The infectivity parameter of FMD virus in the model consists of two intervals: exposure to clinical signs (incubation period), and infectious period. Yoon et al. (2012) estimated the incubation period of FMD virus in the 2010/11 FMD epidemic in the Republic of Korea and found it differed by species. The Lognormal distribution was used to simulate the FMD-incubation period (in days) of beef cattle (μ=6.8, σ=2.3), dairy cattle (μ=6.6, σ=1.9), and pigs (μ=5.5, σ=1.8). However, the ISP software did not provide the Lognormal distribution as an input option for incubation period parameter. Therefore, the cumulative distribution function of the Lognormal distribution was applied as the best approximation. Using @RISK software (version 5.1, Palisade, Ithaca, NY, USA), the Lognormal distribution was simulated 10,000 times to estimate the discrete distribution and range of the incubation period by species (Table 4.1).

Estimates of FMD-infectious periods by species from the 2010/11 FMD epidemic were not available because when an FMD-infected farm was detected, pre-emptive slaughtering was applied to minimise the spread. Therefore, the model assumed an infectious period based on a previous study that identified the infectious period of FMD for cattle and pigs (Mardones et al., 2013a). Following that study, the infectious period was fitted to the Gamma distribution (α=3.969, β=1.107) for cattle and Log logistic distribution (γ=0, β=5.39, α=5.474) for pigs. The same approximation approach used to simulate the incubation periods was applied to the infectious periods for each species. Details of the infectious period and its cumulative probabilities are shown in Table 4.1. The cumulative probabilities of incubation and infectious periods of cattle and pigs were applied to their respective farm types, because the ISP does not simulate within-farm spread of infection.

4.2.4.2 Direct contact (animal movement)

The most common way FMD is spread is by direct contact between FMD-infectious and FMD-susceptible animals (Grubman and Baxt, 2004). In the model, direct contact was defined as animal movement between farms in the study area. Animal movement was described by a Poisson distribution to illustrate the frequency distribution of movements that may occur off an infected farm (Sanson et al., 2011). The input value of animal movements between November 2010 and January 2011 was set based on estimates from a previous study (Yoon et al., 2006). For a given farm, the number of daily animal movements was estimated as a Poisson distribution (λ = 0.25). All animals in the FMD-infected farm were assumed to be infected. For each animal movement, the probabilities of animal movement according to the distance from FMD-infected farm were estimated based on a previous study (Yoon et al., 2006). Details are shown in Table 4.2.

4.2.4.3 Indirect contact

Indirect contact between FMD-infected and FMD-susceptible animals occurs through people, equipment, vehicles, wild animals, or other fomites (Davies, 2002). In this study, indirect contact was incorporated with the local area spread parameter since information about indirect contact in the study area was not available.

4.2.4.4 Local area spread

Local area spread in the model indicated that destination farms were infected because of proximity to an infected farm via indirect or other contacts. The input value for local contact was expressed as the probability that a farm will become infected, given the distance from an infected farm (Stevenson et al., 2013). The radius of local contact was defined as four kilometres from an FMD-infected farm (Table 4.3), and the distance-specific contact probability was based on a previous FMD simulation study in the Republic of Korea (Yoon et al., 2006).

4.2.4.5 Airborne spread

The probability of FMD transmission through the air was associated with the infectiousness and susceptibility of animals, the probability of FMD virus spread through the air, and the distance of the neighbouring farm from an FMD-infected farm. The susceptibility of animals from airborne spread was 0.2 for cattle and 1.0 for pigs (Yoon et al., 2006). The probability of FMD virus spread through the air per day was set as 0.002 (Yoon et al., 2006). The probability of a neighbouring farm being infected through the air at different distances is shown in Table 4.4 (Yoon et al., 2006). The model used meteorological data from the study area during the FMD epidemic to account for wind direction and velocity (KOSTAT, 2013).

4.2.5 Methods to control FMD

The FMD-control strategies simulated in the model were designed based on the reaction plans for an FMD outbreak in the Republic of Korea (MOSPA, 2011). A baseline FMD-control strategy was designed to replicate the 2010/11 FMD epidemic in the study area. Alternative FMD-control strategies were designed by altering control options in the baseline FMD-control strategy. All FMD-control strategies examined in the model included resource constraints, surveillance, pre-emptive slaughtering, vaccination, and movement restriction.

4.2.5.1 Resource constraints

Within the model, the effectiveness of FMD-control measures was subject to resource constraints — for example, there is a limit to the number of farms that can be treated (vaccinated or depopulated) per day — and these constraints can affect the simulation result (Stevenson et al., 2013). The model constrained the number of farms that could be depopulated in a single day to 20 and the number of farms that could be vaccinated to 300, based on events during the 2010/11 FMD epidemic (MOSPA, 2011).

4.2.5.2 Surveillance

Surveillance in the model consisted of two types: passive and active surveillance. Because FMD is listed as a mandatory reported disease in the Republic of Korea, farmers should report any suspicious case to the local veterinary office. The detection probability of passive surveillance, prior to FMD detection, was assumed as 50% because no information about passive surveillance in the study area was available. The detection delay of passive surveillance, which is the period between the onset of clinical signs of FMD and the detection of clinical signs by farmers, was assumed to be zero because farmers check their animals every day. After FMD is diagnosed, surveillance changes from passive to active and a surveillance team surveys the study area. Based on a previous study (Yoon et al., 2006), the detection probability of active surveillance was estimated to be 95%, and the detection of active surveillance was assumed to be seven days, based on the 2010/11 FMD epidemic in the study area (Yoon et al., 2013).

4.2.5.3 Pre-emptive slaughtering

During the 2010/11 FMD epidemic, all susceptible animals within a three kilometre radius of an FMD-infected farm were pre-emptively slaughtered (MOSPA, 2011). Therefore, the baseline radius of the pre-emptive slaughtering area in the model was set to three kilometres. The radius of the pre-emptive slaughtering area was varied in simulated alternative FMD-control strategies, with the radius set at 0.5, one, or five kilometres (Table 4.5). Once a farm was depopulated, it remained empty for the duration of the simulation. Pre-emptive slaughtering began three days after detection of the infected farm, based on the actual response during the 20101/11 FMD epidemic (MOSPA, 2011) and regardless of the radius of the slaughter area.

4.2.5.4 Vaccination

Suppressive vaccination, which is vaccinating all susceptible animals in the study area, was applied during the 2010/11 FMD epidemic. In the model, blanket vaccination was set as the baseline FMD-vaccination method in FMD-control strategies; ring-vaccination, in a band from three to five kilometres around FMD-infected farms, was designed as an alternative. The simulation results of baseline FMD-control strategies with blanket vaccination were compared with the results of the FMD-control strategy with ring vaccination (Table 4.5). Both vaccinations were simulated to start 25 days after first detection to mimic what occurred during the 2010/11 FMD epidemic, when the quantity of correct vaccine type held in reserve was not enough to apply the vaccination until that time (MOSPA, 2011).

The applied vaccines were Decivac® (Intervet International; Kőln, Germany) and Aftopor® (Merial Animal Health Ltd; Surrey, UK). Efficiency was assumed to be 90%, which indicates a vaccinated herd would be FMD immunized with a probability of 90%, based on a literature review (Bates et al., 2003b; Doel, 2003). The infectivity of FMD virus was multiplied by the efficiency of vaccination to calculate the probability of infection on the farm. For all FMD-control strategies, 10 vaccination teams were available; each comprising three paid veterinarians and three volunteer workers. The teams were assumed to vaccinate the susceptible population once in the study area over seven days (MOSPA, 2011).

4.2.5.5 Movement restriction

Movement restriction for preventing direct contacts was applied in the model within a 20 kilometre radius of FMD-infected farms (MOSPA, 2011). Movement restriction comprised two stages: early and late. The early stage indicated a preparation of restriction measures, such as allocating labour resources or setting up check points, and the late stage indicated a restriction period with well-equipped check points. The duration of movement restriction was set based on the actual speed with which restrictions were implemented during the 2010/11 FMD epidemic: three days from detection of the first FMD-infected farm for the early stage, and 97 days (3–100 days) after detection of the first FMD-infected farm for the late stage (MOSPA, 2011). The probability of movement restriction success was varied by stages. The probability of successful movement control in the early stage of the epidemics is relatively low, since it takes time to set up check points for all movement routes. Information about the probability of movement control in the early stage was not available, so it was assumed to be 70%. The probability of movement control success in the late stage was set as 99%, based on a previous study (Yoon et al., 2006). The baseline duration of movement restriction in FMD-control strategies was set to 100 days, based on the control during the 2010/11 FMD epidemic (MOSPA, 2011). In addition, simulation results of alternative FMD-control strategies with movement restrictions of 30 and 60 days were examined (Table 4.5).

4.2.6 Model simulations and outputs

The fitness of the baseline FMD-control strategy was evaluated using two outcomes: descriptive statistics and epidemic curve. Descriptive statistics for the simulated baseline FMD-control strategy were summarised using minimum, maximum, and percentiles. Simulated results comprised the number of farms and animals infected, detected, depopulated, or vaccinated. The median number of simulated FMD-detected farms was then compared with the actual number of FMD-detected farms during the 2010/11 FMD epidemic. An epidemic curve of the cumulative number of FMD-detected farms over time was generated to compare with the 2010/11 FMD epidemic. Once the baseline FMD-control strategy was considered representative of the 2010/11 FMD epidemic in the study area, the effectiveness of other FMD-control strategies was assessed by comparing the descriptive statistics of those simulation results with those of the baseline FMD-control strategy. The model was run for 100 iterations for each FMD-control strategy, including the baseline FMD-control strategy.

4.2.7 Sensitivity analysis

A sensitivity analysis was conducted to determine which parameters in the model most influenced the simulated spread of FMD. As mentioned above, there is uncertainty in parameters because information to determine input values was unavailable. Thus, the sensitivity of the simulation results to changes of FMD-control parameter values was investigated. Control parameters examined here were passive surveillance detection probability, probability of movement restriction, and resource constraints for depopulating farms. For each sensitivity analysis, the input value of one parameter was changed and the others were set to the same values as the baseline FMD-control strategy (Table 4.6).

4.3 Results

4.3.1 Baseline model

The median number of FMD-detected farms simulated by the model for the baseline strategy was 299 (range 192–452) farms, which was the same as the number of FMD-detected farms reported during the 2010/11 FMD epidemic (Table 4.7). The median number of FMD-infected farms simulated by the model was 299 (range 193–467) farms; the number of FMD-infected farms during the 2010/11 FMD epidemic was not available. The median number of depopulated farms in the simulation was 611 (range 324–905) farms; however, the number of depopulated farms during the 2010/11 FMD epidemic was 1302. The median number of vaccinated farms in the simulation was 1878 (range 1757–1947); the number of vaccinated farms during the 2010/11 FMD epidemic was not available. The median number of animals simulated was 53,457 FMD-infected (range 35,873–79,853); 51,186 FMD-detected (range 35,690–76,130); 52,979 depopulated (range 21,356–99,173); and 124,162 vaccinated (range 101,705–152,519; Table 4.7). The simulated cumulative number of FMD-detected farms increased rapidly until day 40 and then flattened; this was similar to the actual FMD epidemic, which was located between the 5th and 95th percentile of simulated results for most of the epidemic (Figure 4.3). The distribution of FMD-susceptible farms and simulated FMD-infected farms is shown in Figure 4.4 and 4.5.

4.3.2 Alternative strategies

When the three kilometre pre-emptive slaughtering area was reduced (0.5 and one kilometre slaughtering strategies) or the 100-day movement restriction was reduced (30-day stop movement strategy), the disease was not controlled at least 95% of the time during the 100-day simulation period. The median epidemic durations were 77 (range 49–100) for the baseline strategy, 75 (range 49–99) for the five kilometre slaughtering strategy, 98 (range 95–100) for the 60-day stop movement strategy, and 79 (range 51–100) for the ring vaccination strategy (Table 4.8).

The median number of simulated FMD-infected farms and animals decreased as the radius of pre-emptive slaughtering area increased; thus, the median number of simulated FMD-infected farms was 872 (range 821–968) for the 0.5 kilometre slaughtering strategy, 604 (range 411–686) for the one kilometre slaughtering strategy, and 252 (range 177–365) for the five kilometre slaughtering strategy (Table 4.9). The simulated median number of FMD-infected animals for 0.5, one, and five kilometre slaughtering strategies was 101,820 (range 79,820–120,580); 83,173 (range 52,277–101,760); and 47,826 (range 27,724–76,462), respectively.

The median number of simulated FMD-infected farms and animals decreased as the duration of movement restriction increased. With the 30-day and 60-day stop movement strategy, the median number of simulated FMD-infected farms were from 890 (range 723–1100) and 722 (range 583–822), respectively. The median number of simulated FMD-infected animals for 30-day and 60-day movement strategies were 94,736 (range 72,892–116,550) and 80,932 (range 45,771–108,040), respectively.

When ring vaccination was applied, the median number of simulated FMD-infected farms was 308 (range 195–481) and the median number of simulated FMD-infected animals was 55,987 (range 37,141–82,159).

The median number of simulated depopulated farms was 858 (range 794–690) for the 0.5 kilometre slaughtering strategy, 704 (range 528–864) for the one kilometre slaughtering strategy, and 1002 (range 748–1210) for the five kilometre slaughtering strategy (Table 4.10). The median number of simulated depopulated animals for 0.5 kilometre slaughtering, one kilometre slaughtering, and five kilometre slaughtering strategies were 98,932 (range 79,203–119,050), 59,625 (range 33,375–82,352), and 76,596 (range 55,514–107,760), respectively.

With the 30-day and 60-day stop movement strategy, the median number of simulated depopulated farms was 1232 (range 1065–1307) and 1232 (range 1112–1345), respectively. The median number of depopulated animals for 30-day and 60-day movement strategies was 88,064 (range 58,585–108,405) and 86,452 (range 60,848–121,559), respectively.

When ring vaccination was applied, the median number of simulated depopulated farms was 654 (range 575–915) and the median number of FMD-infected animals was 66,187 (range 39,911–89,581).

The median number of simulated vaccinated farms was 1970 (range 1771–2036) for the 0.5 kilometre slaughtering strategy, 1954 (range 1875–2011) for the one kilometre slaughtering strategy, and 1805 (range 1510–1936) for the five kilometre slaughtering strategy (Table 4.11). The median number of simulated vaccinated animals for 0.5, one, and five kilometre slaughtering strategies was 157,926 (range 131,694–167,262), 153,412 (range 119,321–164,593), and 100,465 (range 83,725–128,248), respectively.

With the 30-day and 60-day stop movement strategy, the median number of simulated vaccinated farms was 2010 (range 1906–2090) and 1888 (range 1759–1967), respectively. The median number of simulated vaccinated animals for 30-day and 60-day movement strategies was 130,473 (range 103,764–161,705) and 124,691 (range 101,775–155,050), respectively.

When ring vaccination was applied, the median number of simulated vaccinated farms was 1191 (range 1039–1555) and the median number of simulated FMD-infected animals was 69,909 (range 58,784–98,928).

4.3.3 Sensitivity analysis

Sensitivity analysis indicates the simulation results were insensitive to most changes in parameters. Changes in the median number of FMD-infected farms in response to altering the passive surveillance detection probability and the probability of movement restriction parameters were less than 20% (Table 4.12). The highest median number of FMD-infected farms was 338 (range 229–498) for 10% passive surveillance detection probability and 312 (range 223–501) for 10% movement restriction probability. The most influential parameter was the number of farms depopulated per day; when this decreased from 20 to 10, the median number of simulated infected farms increased by 8%, from 299 (range 193–467) in the baseline to 324 (range 218–498), but when it increased from 20 to 50, the median number of simulated infected farms decreased by about 15%, to 257 (range 171–427).

4.4 Discussion

A simulation model was constructed to replicate the temporal and spatial progression of the 2010/11 FMD epidemic in the city of Andong, Republic of Korea. The model was representative of the 2010/11 FMD epidemic in its prediction of two outcomes: the number of FMD-detected farms and the epidemic curve. As a result, our model could be used to represent the 2010/11 FMD epidemic in the study area.

The simulation software used in the study, InterSpread Plus (ISP), has been validated by comparing it with other simulation models (Sanson et al., 2011). When three simulation software applications, AusSpread (Garner and Beckett, 2005), ISP, and the North American Animal Disease Spread Model (Harvey et al., 2007), used identical input data, there was no significant difference in simulation results among the three applications. This consistency of ISP with other simulation software increases the confidence in predictions made by our model.

Information was not available concerning animal movements in the study area during the epidemic. We therefore used results from Yoon et al. (2006), who estimated distance-specific animal movement frequency by estimating the distribution and parameter(s) that enabled the disease spread model to produce results that best simulated the 2001 FMD epidemic in the Republic of Korea. Nevertheless, the impact of uncertainty in the animal movement parameter on the simulation results was probably small, because less than 3% of simulated transmission occurred through direct contact.

Vaccination was simulated to begin 25 days after the first detection of an FMD-infected farm, based on actual events during the 2010/11 FMD epidemic (MOSPA, 2011). Earlier vaccination could lead to more effective control. Sanson et al. (2014) described the efficacy of early vaccination using an FMD simulation model in Alberta, Canada. The study found that when vaccination was applied 10 days after detection of an FMD-infected farm, the simulated duration of the FMD epidemic was reduced by 11 days. The early application of blanket vaccination is only possible when the vaccine reserve is enough to vaccinate all FMD-susceptible animals in the target area. In practice, it is hard to stock sufficient reserves of FMD vaccines to apply an early vaccination over such a large area, so the deficiency of vaccine reserve could delay the application of blanket vaccination, resulting in a larger and more protracted epidemic.

The smaller 0.5 and one kilometre slaughtering and 30 day stop movement did not control FMD within the 100-day simulation period. If the model had been run longer than 100 days, the median number of FMD-infected farms and animals for those FMD-control strategies would have increased. Thus, results from those FMD-control strategies should be interpreted as conservative estimates of what would happen.

The reported number of depopulated farms in the study area during the FMD epidemic was 1302, whereas the median number of simulated depopulation farms for the baseline strategy was 611. This difference may be because simulated FMD-infected farms were located mainly in the northwest of the study area, whereas some of the actual FMD-infected farms were located outside this area (Figure 4.4). As a result, simulations would have more farms located within a three kilometre pre-emptive slaughtering area of FMD-infected farms than if the FMD-infected farms were more dispersed, resulting in an underestimate of depopulated farms. The number of FMD-susceptible farms was 1077 within a three kilometre radius of an FMD-infected farm (Figure 4.5). If the locations of simulated FMD-infected farms were more dispersed, and therefore more accurately reflected the actual epidemic, the simulated number of depopulated farms would have increased.

Ring vaccination might be applied as an alternative to control of FMD spread because its epidemiologic effectiveness, such as the duration of FMD epidemic or the number of FMD-infected farms and animals, was similar to that of blanket vaccination. The advantage of ring vaccination is that it requires fewer resources (e.g. labour or equipment) than blanket vaccination, because only animals in pre-defined vaccination area are vaccinated. These resources could then be allocated to other FMD-control measures such as movement restriction or pre-emptive slaughtering. The disadvantage of ring vaccination is that it is not straightforward to define the vaccination area where farms are crowded, because FMD may spread rapidly and the vaccination area may change frequently as farms are confirmed with FMD-infection. Furthermore, from the public's perspective it would be more difficult to understand the application of ring vaccination rather than area-wide blanket vaccination.

The FMD-control strategy with a five kilometre versus a three kilometre or less radius of an FMD-infected farm as a pre-emptive slaughtering area simulated the least number of FMD-infected farms and animals; however, the disadvantage of this strategy is that it requires a large amount of resources to cull and dispose of animals. Moreover, the number of culled animals is an important issue from a public perception perspective. Mass culling of animals as pre-emptive slaughtering might not be acceptable to the public due to its perceived cruelty. The culling of animals, particularly those without clinical signs of disease, may also result in a negative impact on mental health of farmers with FMD-affected farms. During the 2001 FMD epidemic in the Netherlands, farmers whose farms were depopulated during pre-emptive slaughtering suffered from stress or depression (Van Haaften et al., 2004). Our study determined how changes in the pre-emptive slaughtering area would affect final outbreak size. As discussed above, when the pre-emptive slaughtering area was reduced to a 0.5 or one kilometre radius, FMD epidemics were not controlled within the 100-day evaluation period. If the radius of the pre-emptive slaughtering area was reduced from five kilometres to one kilometre, then the median number of simulated FMD-infected farms increased 2.5 times. Therefore, the social impact of slaughtering must be offset by the need to control the epidemic rapidly.

Like previous FMD modelling research (Bates et al., 2003b; Thrusfield et al., 2005), the current study emphasized that available labour and equipment resources for pre-emptive slaughtering were an important parameter in the simulated number of FMD-infected farms. The number of simulated FMD-infected farms decreased as the number of depopulated farms per day increased, and vice versa. Because resources for applying disease control measures are limited, it is important to allocate these efficiently. The FMD-control strategy with ring vaccination might be more useful than blanket vaccination because the saved resources might be used for pre-emptive slaughtering. Furthermore, the results of this simulation point out the need for the government to ensure sufficient resources are available to decrease the number of FMD-infected farms and animals and decrease the duration of the epidemic.

4.5 Conclusions

The simulation model was representative of the 2010/11 FMD epidemic in the city of Andong, Republic of Korea and was used to evaluate the effectiveness of alternative FMD-control strategies. Of the alternative control strategies examined here, a pre-emptive slaughter area of radius five kilometres around an infected farm, paired with 100-days of movement restriction and vaccinating all FMD-susceptible animals in the study area, was the most effective strategy for controlling FMD. However, the resources required for the five kilometre slaughtering strategy, such as labour and equipment, might be greater than for other FMD-control strategies. Ring vaccination in a band from three to five kilometres around FMD-infected farms might be applied as an alternative because it provided similar effectiveness to that of blanket vaccination with fewer resources; however, it has weaknesses associated with public perception and communication. Therefore, in addition to an epidemiologic analysis, an economic analysis of FMD-control strategies should be performed before making a recommendation regarding FMD-control strategies.

Table 4.1. Interval from exposure to incubation and infectious period and its cumulative probability as used in the foot-and-mouth disease (FMD) simulation model.

Period	0.01	0.05	0.10	0.25	0.50	0.75	0.90	0.95	0.99	1.00
Incubation (days)*										
Beef	3	4	4	5	6	8	10	11	14	18
Dairy	3	4	4	5	6	8	9	10	12	15
Pig	2	3	3	4	5	6	8	9	11	14
Infectious (days)#										
Cattle	1	1	2	3	4	6	7	9	11	15
Pig	2	3	4	4	5	7	8	9	12	22

Source: *H. J. Yoon et al., 2012, # F. Mardones et al., 2010.

Table 4.2. Probability of a movement being within a distance band in the city of Andong, Republic of Korea.

Distance from an infected farm (meters)	Probability
0 to < 5,000	0.30
5,000 to < 10,000	0.55
Over 10,000 *	0.15

Source: H. J. Yoon et al., 2006.

* The distance category, 10,000 to < 15,000 and 15,000 to < 30,000, in Yoon’s study was modified as over 10,000 since the study area in the present study was smaller than Yoon’s study area.

Table 4.3. Daily probability that susceptible animals on a farm will be infected by local area spread, based on proximity to an infected farm in the city of Andong, Republic of Korea.

Distance from an infected farm (metres)	Daily probability of infection
0 to 1000	0.010
1001 to 2000	0.005
2001 to 3000	0.002
3001 to 4000	0.001

Source: H. J. Yoon (personal communication, 2011).

Table 4.4. Daily probability that susceptible animals on a farm will be infected by airborne spread based on proximity to an infected farm in the city of Andong, Republic of Korea.

Distance from an infected farm	Probability of infection
0 to < 1000 m	0.000100
1000 to < 3000 m	0.000020
3000 to < 5000 m	0.000010
5000 to < 10,000 m	0.000025

Source: H.J. Yoon et al. 2006.

Table 4.5. Details of baseline strategy and each alternative foot-and-mouth disease (FMD) control strategy.

	Pre-emptive slaughtering area (kilometre)	Movement restriction (days)	Vaccination
Baseline	3	100	Suppressive*
Alternatives			
Different radius of pre-emptive slaughtering area			
0.5 kilometre slaughtering	0.5	100	Suppressive
1 kilometre slaughtering	1	100	Suppressive
5 kilometre slaughtering	5	100	Suppressive
Different duration of movement restriction			
30 day stop movement	3	30	Suppressive
60 day stop movement	3	60	Suppressive
Different vaccination			
Ring vaccination	3	100	Ring#

* Suppressive vaccination: vaccinating all FMD-susceptible animals in the study area.

Ring vaccination: vaccinating all FMD-susceptible animals in a band between three and five kilometres of a FMD-infected farm.

Table 4.6. Parameters examined in sensitivity analysis.

Parameters	Input value				
Passive surveillance detection probability (%)	10	30	50#	70	90
Probability of movement restriction in the first 3 days (%)	10	30	50	70#	90
Resource constraint for depopulating farms (farms)	10	20#	30	40	50

Default input value.

Table 4.7. Simulated number of infected, detected, and depopulated farms and animals for a simulated baseline foot-and-mouth disease (FMD) control strategy to control the 2010/11 FMD epidemic in the city of Andong, Republic of Korea.

	Number of farms					Number of animals				
	Min	Q1	Med	Q3	Max	Min	Q1	Med	Q3	Max
Infected	193	237	299	353	467	35,873	46,695	53,457	64,656	79,853
Detected	192	237	299	351	452	35,690	45,910	51,186	63,135	76,130
Depopulated	324	532	611	692	905	21,356	39,540	52,979	68,014	99,173
Vaccinated	1757	1823	1878	1902	1947	101,705	114,096	124,162	132,527	152,519

During the 2010/11 epidemic in the city of Andong, Republic of Korea, the actual number of FMD-detected farms = 299; FMD-detected animals = 59,902; depopulated farms = 1302; and depopulated animals = 142,618.

Min: minimum number of simulation result, Q1: 25th percentile of simulation result, Med: median number of simulation result, Q3: 75th percentile of simulation result, and Max: maximum number of simulation result.

Table 4.8. Simulated foot-and-mouth disease (FMD) epidemic duration for differing radius of pre-emptive slaughtering area, duration of movement restriction, and application of vaccination for FMD-control strategies to control the 2010/11 FMD epidemic in the city of Andong, Republic of Korea.

	Duration of FMD epidemics (days)				
	Min	Q1	Med	Q3	Max
Baseline#	49	62	77	93	100+
Radius of pre-emptive slaughtering (kilometre)					
0.5	100	100	100	100	100
1	99	100	100	100	100
5	49	56	75	80	99
Duration of movement restriction (days)					
30	98	100	100	100	100
60	95	96	98	99	100
Application of vaccination					
Ring	51	65	79	95	100

The actual duration of the 2010/11 epidemic in the city of Andong, Republic of Korea, was 58 days.

Baseline FMD-control strategy: three kilometre pre-emptive slaughtering area, 100 day movement restriction, and blanket vaccination.

Min: minimum number of simulation result, Q1: 25th percentile of simulation result, Med: median number of simulation result, Q3: 75th percentile of simulation result, and Max: maximum number of simulation result.

+Note: values of 100 indicate the epidemic was not controlled by the end of the model simulation.

Table 4.9. Simulated number of foot-and-mouth disease (FMD) infected farms and animals for differing pre-emptive slaughtering area, duration of movement restriction, and application of vaccination for FMD-control strategies to control the 2010/11 FMD epidemic in the city of Andong, Republic of Korea

Strategy	Number of infected farms					Number of infected animals				
	Min	Q1	Med	Q3	Max	Min	Q1	Med	Q3	Max
Baseline#	193	237	299	353	467	35,873	46,695	53,457	64,656	79,853
Radius of pre-emptive slaughtering (kilometre)										
0.5	821	863	872	932	968	79,820	93,793	101,820	109,910	120,580
1	411	559	604	644	686	52,277	70,852	83,173	88,956	101,760
5	177	225	252	308	365	27,724	41,372	47,826	55,806	76,462
Duration of movement restriction (days)										
30	723	866	890	1000	1100	72,892	83,402	91,736	99,130	116,550
60	583	641	722	740	822	45,771	64,508	80,932	90,339	108,040
Application of vaccination										
Ring	195	241	308	369	481	37,141	48,127	55,987	66,157	82,159

The actual number of FMD-confirmed farms was 299 and the actual number of FMD-confirmed animals was 59,902 during the 2010/11 FMD epidemic in the city of Andong, Republic of Korea.

Baseline FMD-control strategy: three kilometre pre-emptive slaughtering area, 100 day movement restriction, and blanket vaccination.

Min: minimum number of simulation result, Q1: 25th percentile of simulation result, Med: median number of simulation result, Q3: 75th percentile of simulation result, and Max: maximum number of simulation result.

Table 4.10. Simulated number of depopulated farms and animals for differing pre-emptive slaughtering area, duration of movement restriction, and application of vaccination for FMD-control strategies to control the 2010/11 FMD epidemic in the city of Andong, Republic of Korea.

Strategy	Number of depopulated farms					Number of depopulated animals				
	Min	Q1	Med	Q3	Max	Min	Q1	Med	Q3	Max
Baseline#	324	532	611	692	905	21,356	39,540	52,979	68,014	99,173
Radius of pre-emptive slaughtering (kilometre)										
0.5	794	838	858	900	960	79,203	89,668	98,932	106,130	119,050
1	528	666	704	768	864	33,375	49,949	59,625	64,423	82,352
5	748	888	1002	1100	1210	55,514	69,893	76,596	89,848	107,760
Duration of movement restriction (days)										
30	1065	1142	1232	1283	1307	58,585	78,513	88,064	93,777	108,405
60	1112	1178	1232	1247	1345	60,848	78,699	86,452	104,194	121,559
Application of vaccination										
Ring	575	622	654	796	915	39,911	51,165	66,187	73,902	89,581

The actual number of depopulated farms was 1302 and the actual number of depopulated animals was 142,618 during the 2010/11 FMD epidemic in the city of Andong, Republic of Korea.

Baseline FMD-control strategy: three kilometre pre-emptive slaughtering area, 100 day movement restriction, and blanket vaccination.

Min: minimum number of simulation result, Q1: 25th percentile of simulation result, Med: median number of simulation result, Q3: 75th percentile of simulation result, and Max: maximum number of simulation.

Table 4.11. Simulated number of vaccinated farms and animals for differing pre-emptive slaughtering area, duration of movement restriction, and application of vaccination for FMD-control strategies to control the 2010/11 FMD epidemic in the city of Andong, Republic of Korea.

Strategy	Number of vaccinated farms					Number of vaccinated animals				
	Min	Q1	Med	Q3	Max	Min	Q1	Med	Q3	Max
Baseline[#]	1757	1823	1878	1902	1947	101,705	114,096	124,162	132,527	152,519
Radius of pre-emptive slaughtering (kilometre)										
0.5	1771	1941	1970	1990	2036	131,694	149,192	157,926	161,385	167,262
1	1875	1912	1954	1975	2011	119,321	136,912	153,412	156,598	164,593
5	1510	1770	1805	1838	1936	83,725	93,669	100,465	108,022	128,248
Duration of movement restriction (days)										
30	1906	1972	2010	2031	2130	103,764	118,727	130,473	138,735	161,705
60	1759	1834	1888	1932	1967	101,775	114,372	124,691	133,767	155,050
Application of vaccination										
Ring	1039	1140	1191	1432	1555	58,784	64,808	69,909	86,341	98,928

The actual number of vaccinated farms and animals during the 2010/11 FMD epidemic in the city of Andong, Republic of Korea was not available.

Baseline FMD-control strategy: three kilometre pre-emptive slaughtering area, 100 day movement restriction, and blanket vaccination.

Min: minimum number of simulation result, Q1: 25th percentile of simulation result, Med: median number of simulation result, Q3: 75th percentile of simulation result, and Max: maximum number of simulation.

Table 4.12. Simulated number of infected farms using the baseline foot-and-mouth disease (FMD) control strategy for different parameter values of the FMD-control strategy to control the 2010/11 FMD epidemic in the city of Andong, Republic of Korea.

	Number of infected farms				
	Min	Q1	Med	Q3	Max
Detection probability of passive surveillance					
0.10	229	274	338	379	498
0.30	209	249	311	360	472
0.50#	193	237	299	353	467
0.70	179	211	274	338	442
0.90	171	204	269	324	431
Success probability of early movement restriction					
0.10	223	267	312	374	501
0.30	216	249	307	364	495
0.50	209	241	302	359	482
0.70#	193	237	299	353	467
0.90	185	229	284	340	452
The number of farms handled per day					
10	218	252	324	374	498
20#	193	237	299	353	467
30	182	223	281	341	452
40	175	219	269	322	439
50	171	208	257	310	427

Default input value.

Min: minimum number of simulation result, Q1: 25th percentile of simulation result, Med: median number of simulation result, Q3: 75th percentile of simulation result, and Max: maximum number of simulation result.

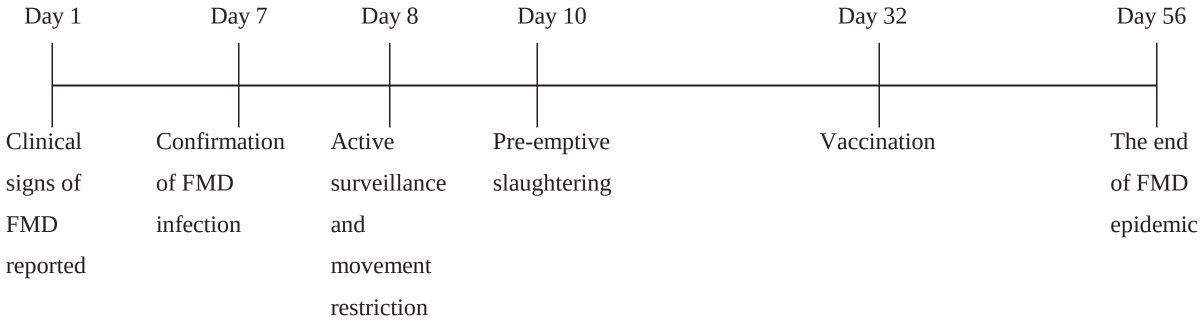

Figure 4.1. Timeline of the 2010/11 foot-and-mouth disease (FMD) epidemic in the city of Andong, Republic of Korea, and the commencement date of active surveillance, movement restriction, pre-emptive slaughtering, and vaccination (Day 1: 23 November, 2010).

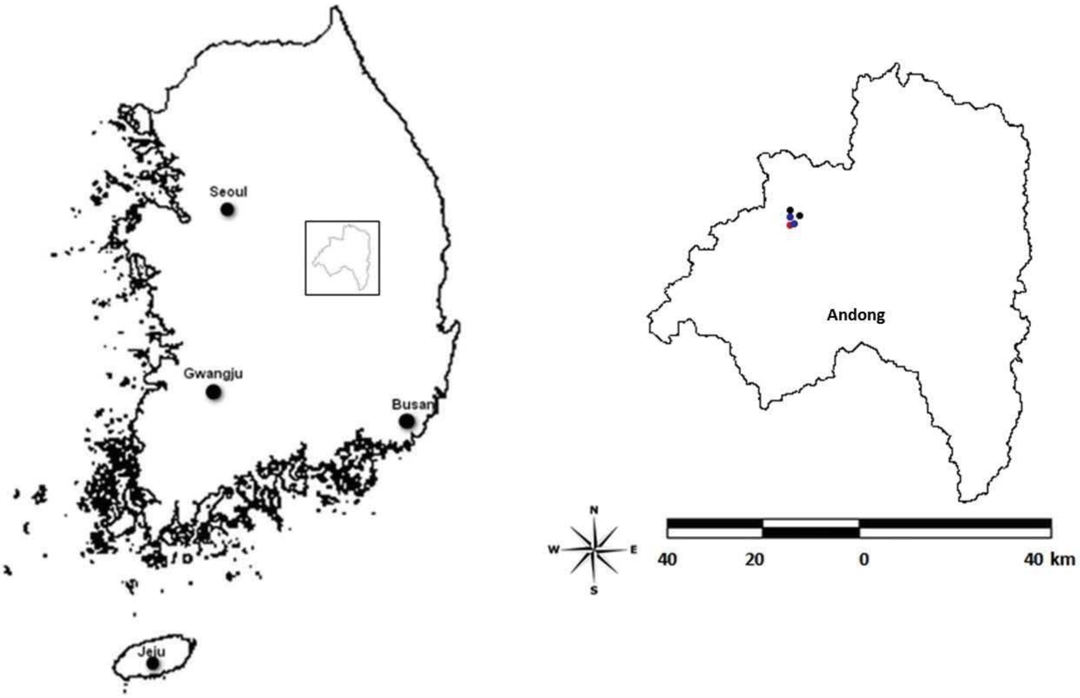

Figure 4.2. Map of index farms for spatial and stochastic simulation models of foot-and-mouth disease (FMD) in the city of Andong, Republic of Korea. Inset: map of the Republic of Korea showing the location of the study area (FMD-infected farm on day 1 (red), day 2 (blue) and day 3 (black)).

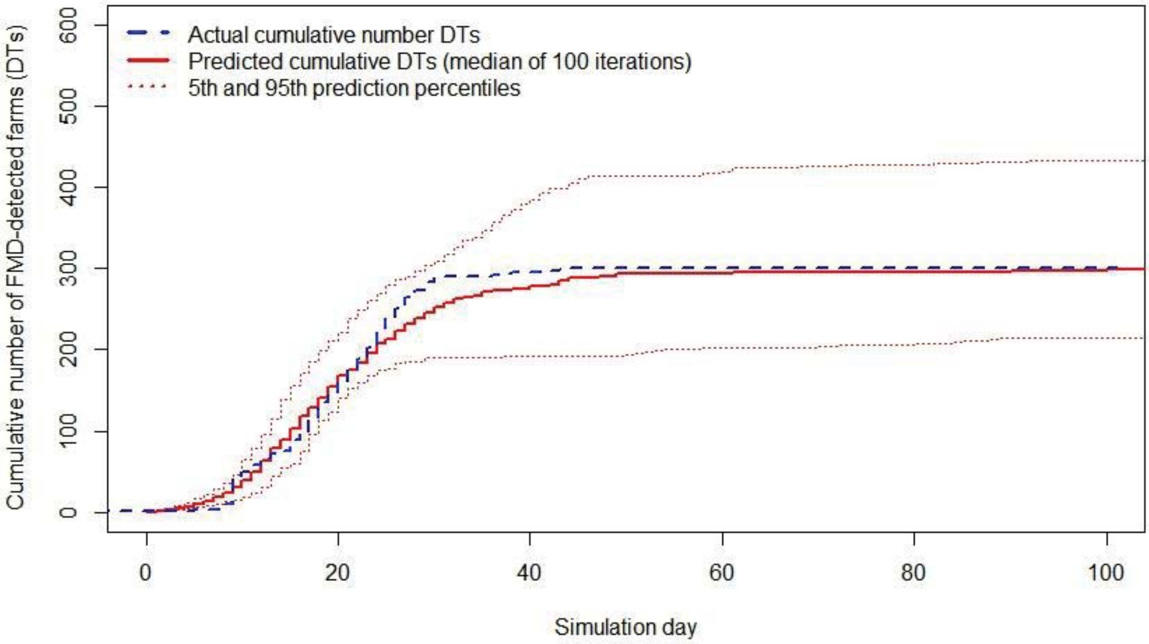

Figure 4.3. Cumulative number of foot-and-mouth disease (FMD) detected farms and simulated FMD-detected farms with 5th, 50th and 95th percentiles of baseline FMD-control strategy for controlling the 2010/11 FMD epidemic in the city of Andong, Republic of Korea (DTs: the number of FMD-detected farms).

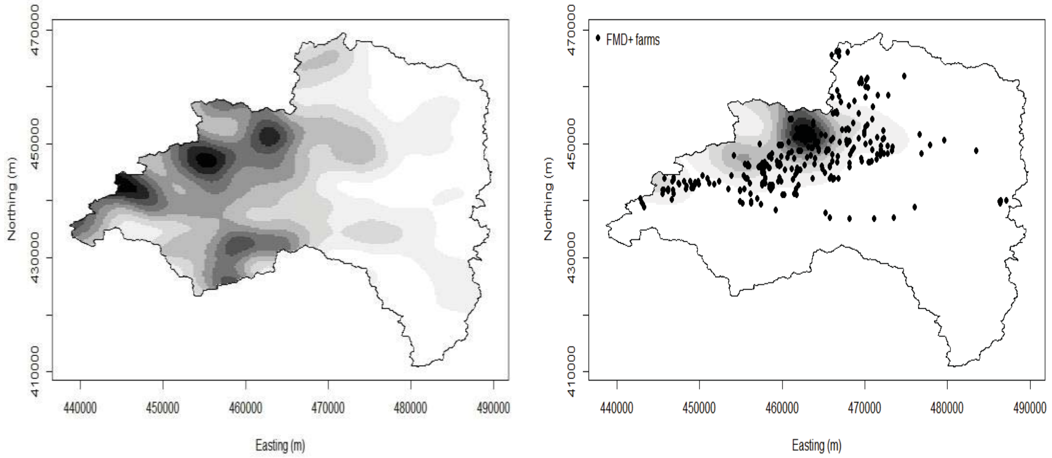

Figure 4.4. Kernel-smoothed surface of the FMD-susceptible farms (left) and the simulated FMD-infected farms (right) per square kilometre in the city of Andong, Republic of Korea. Darker areas indicate higher density of farms; black points show the location of farms actually infected during the 2010-2011 FMD outbreak.

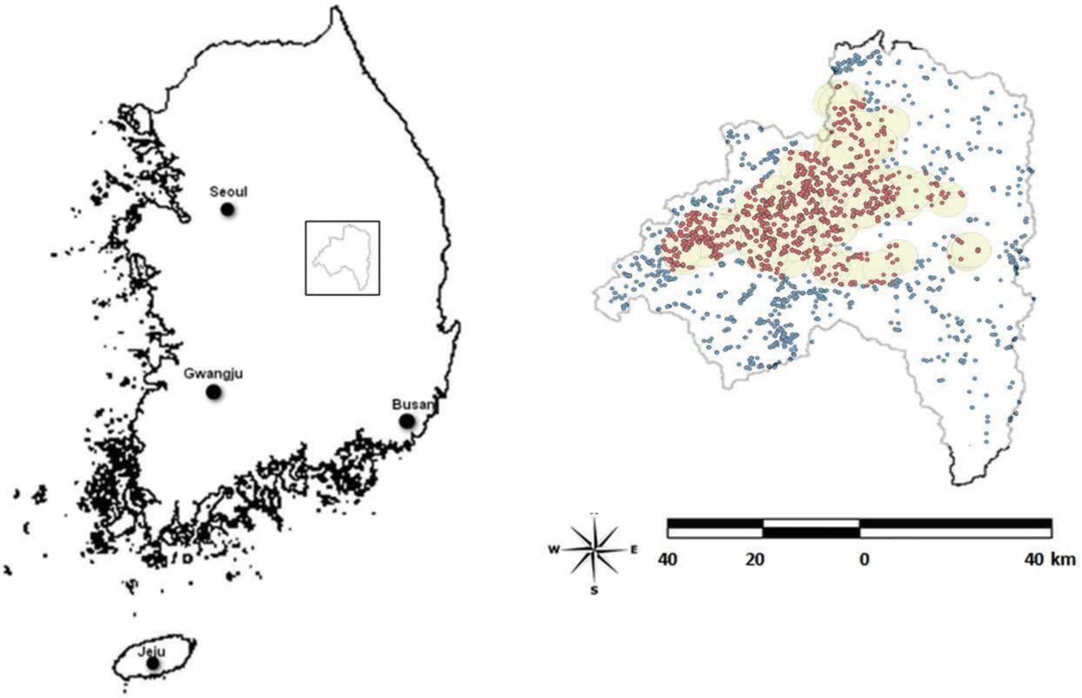

Figure 4.5. Map of the distribution of all FMD-susceptible farms located outside (blue dots) or inside (red dots) a three kilometre radius of FMD-infected farms (yellow circles) in the city of Andong, Republic of Korea.

Chapter V

5 The cost-effectiveness of alternative control measures against the 2010-2011 epidemic of foot-and-mouth disease (FMD) in the city of Andong, Republic of Korea

EuTteum Kim, Tim Carpenter, Sarah Rosanowski, Mark Stevenson, Naomi Cogger

Abstract

The cost-effectiveness of foot-and-mouth disease (FMD) control strategies was evaluated using a simulation model fitted to the 2010/11 FMD epidemic in the city of Andong, Republic of Korea. Seven FMD-control strategies were evaluated with respect to the direct cost of the FMD-control strategy, such as slaughtering, movement restriction, and vaccination. All strategies included pre-emptive slaughtering, movement restriction, and vaccination; however, levels of each control option were different. The simulated median cost of the baseline FMD-control strategy (three kilometre radius for pre-emptive slaughtering area, 100 days of movement restriction, and vaccinating all FMD-susceptible animals in the study area) was estimated at USD 99.7 million. When a five kilometre radius for the vaccination area was applied (other control measures were same as the baseline strategy), the simulated median cost was reduced by USD 18.6 million, from USD 99.7 to USD 81.1 million. The simulated median costs were USD 107.6 million for a five kilometre radius slaughtering area and USD 168.8 million for 60 days of movement restriction. The cost of the FMD-control strategy decreased when the number of farms depopulated per day, the probability of passive surveillance being effective, or the probability of the successful implementation of movement restriction increased. Cost-effectiveness analysis represents a tool for evaluating the financial consequence of FMD-control strategies by comparing the cost of control strategies for a specific area.

5.1 Introduction

Foot-and-mouth disease (FMD) is one of the most economically important diseases in livestock because it can spread rapidly to susceptible animals, resulting in a massive outbreak in a short period and a loss of export markets in previously FMD-free countries (Knight-Jones and Rushton, 2013). The major direct loss from the disease is a decrease in productivity, such as reduced milk production, increased mastitis, lameness in draught animals, or decreased weight gain in growing animals (James and Rushton, 2002). Knight-Jones and Rushton (2013) estimated the global annual financial impact of FMD due to decreased productivity as USD 7.6 billion. The major indirect loss is due to bans on exporting animals and animal products. The Australian government estimated revenue losses due to lost export markets associated with an FMD outbreak would be approximately AUD 52 billion over 10 years (Anomymous, 2013). Similarly, the New Zealand government estimated lost export earnings due to an FMD outbreak would be approximately NZD 6.7 billion if exports were stopped for 10 months (Forbes and van Halderen, 2014).

In addition to the direct and indirect losses caused by FMD, operational costs would be incurred during an FMD eradication program; these costs would include, for example, compensation, vaccinating FMD-susceptible animals, or culling infected or high-risk animals and disposing of the carcasses. Rushton et al. (2002) estimated that if vaccination had been used to immunize FMD-susceptible animals during the 2001 FMD outbreak in the United Kingdom the cost of vaccination would have been GBP 134 million. Furthermore, farmers whose animals are vaccinated may be paid compensation because the animal products may not be sold. During the 2001 outbreak, vaccination was not applied as a control measure; instead, the government paid GBP 1.1 billion as compensation to farmers with FMD-affected farms (Thompson et al., 2002).

In the Republic of Korea, control and eradication options in the event of an FMD outbreak are based on three strategies: pre-emptive depopulation, movement restriction, and blanket vaccination (MOSPA, 2011). The epidemiologic and economic effectiveness of these strategies has been examined in several studies (Jalvingh et al., 1999; Bates et al., 2003a; Yoon et al., 2006; Boklund et al., 2013). However, a literature review found no research on the financial consequences of different FMD-control strategies in the Republic of Korea. The objective of this study was to explore the financial consequences of alternative FMD-control strategies based on simulation results for the 2010/11 FMD epidemic in the city of Andong, Republic of Korea. The financial consequences of FMD-control strategies were used to measure the economic criterion in multi-criteria decision analysis of FMD-control strategies.

5.2 Materials and methods

5.2.1 Cost-effectiveness analysis and FMD-control strategies

A cost-effectiveness (CE) analysis was performed to assess the financial consequences of FMD-control strategies. The baseline cost was estimated based on the actual FMD-control strategy applied during the 2010/11 FMD epidemic in the Republic of Korea. This baseline strategy consisted of a pre-emptive slaughter area with a three kilometre radius, 100 day movement restriction, and vaccination of all FMD-susceptible animals (blanket vaccination) in the country (MOSPA, 2011). Alternative levels of these control measures for the baseline FMD-control strategy were simulated to evaluate the effectiveness of alternative FMD-control strategies. Changes in control measures were: 1) pre-emptive slaughtering within a radius of 0.5, one and five kilometres of an infected farm; 2) movement restriction duration of 30 days and 60 days; 3) ring vaccination in a band from three to five kilometres around an FMD-infected farm (Table 5.1). Simulated costs of the FMD-control strategies that eradicated FMD in the study area were compared

5.2.2 Study population

The study area was the city of Andong, Republic of Korea, the index city of the 2010/11 FMD epidemic. When registered in October 2010, the FMD-susceptible population in the city consisted of 2364 Korean beef cow farms, six dairy cow farms, 87 pig farms, five sheep farms, and two deer farms (MOSPA, 2011). The mean farm size was 20 for beef and 1167 for pigs. Dairy, sheep, and deer farms were excluded from modelling because there was no available information for those farms and no FMD-infection was confirmed in those farms during the 2010/11 FMD epidemic. Farm information, including farm type and the number of animals on the farm, was collected from the Korean National Statistics (KOSTAT, 2013).

5.2.3 Cost information

Direct costs for FMD-control measures were calculated for compensation for animal loss due to culling, carcass disposal, movement restriction, and vaccination. Indirect costs of FMD-control strategy, such as export bans or decreases in domestic animal products consumption, were excluded in the study because they were beyond its scope. All cost information was obtained from the Ministry of Security and Public Administration and Statistics Korea. All economic analyses were based on the Korean National Statistics (KOSTAT, 2011) calculations for the number of animals per farm, with the mean number of cattle on a beef farm being 20 and the mean number of pigs per farm being 1167. Compensation was paid to farmers whose animals were culled to control FMD spread. The compensation costs for culled animals were the market value of a healthy animal at the time of culling. According to the national statistics on livestock prices (KOSTAT, 2011), the market value of an adult beef cow in the Republic of Korea in 2010 was USD 4140 for a male weighing over 600 kilograms, USD 3767 for a female weighing over 600 kilograms, USD 2043 for a male weighing between 350 and 600 kilograms and USD 4030 for a female weighing between 350 and 600 kilograms. The market value for a calf was USD 1779 for a male weighing less than 350 kilograms and USD 1688 for a female weighing less than 350 kilograms. The market values of pigs were USD 71 for farrowing pigs, USD 110 for weaning pigs, USD 260 for growing or finishing pigs, and USD 900 for adult pigs. The compensation cost for a beef farm was USD 60,585 and USD 221,994 for a pig farm (Table 5.2). The total compensation cost for an FMD-control strategy was calculated based on the number of depopulated animals.

The cost for carcass disposal was estimated based on the assumption that all culled animals were buried in disposal areas. A disposal area was intensively disinfected and cleaned to prevent contaminating the environment. The costs for disposal areas consisted of equipment costs for digging, cleaning, and disinfecting the disposal area, and labour costs. During the 2010/11 FMD epidemic, one disposal area could handle two cattle farms or one-third of a pig farm (MOSPA, 2011). The cost for one disposal area was USD 9643; details are shown in Table 5.3. The total cost for carcass disposal per FMD-control strategy was calculated based on the number of depopulated farms.

The cost for movement restriction was for operating a road office, which was used for watching and controlling movements of live animals and animal products. Each office was located on the road to an FMD-infected area and every movement in and out of the area was inspected. The road offices were well equipped to clean and disinfect vehicles moving in and out of the FMD-infected area. Thus, the cost for operating a road office included equipment, disinfectant, and labour. The cost for one road office for 100 days (baseline strategy) was USD 22,081; details are shown in Table 5.4. During the 2010/11 FMD epidemic, 21 road offices were operated to control movements of live animals and animal products in the study area (MOSPA, 2011). The total cost for movement restriction per FMD-control strategy was calculated based on the duration of the movement restriction.

Vaccination cost was estimated based on the assumption that 10 vaccination teams covered the study area for 7 days and each team consisted of three paid veterinarians and three volunteer workers

(MOSPA, 2011). The cost for vaccination was divided into two parts: administration and vaccine cost. The administration cost for completing vaccination was USD 59,190, which included labour and equipment costs. The vaccine cost was USD 4 per animal (MOSPA, 2011). Details of vaccination costs are shown in Table 5.5. The total vaccination cost per FMD-control strategy was calculated based on the number of vaccinated animals.

5.2.4 Simulation analysis

The simulated results are described in detail in Chapter 4. Briefly, FMD spread for FMD-control strategies was simulated using disease spread simulation software InterSpread Plus (ISP) (EpiCentre, Palmerston North, New Zealand). The ISP model is a state-transition simulation tool that has previously been used to simulate the spread of FMD between farms in the Republic of Korea (Yoon et al., 2006) and in the United Kingdom (Morris et al., 2001; Thompson et al., 2002). For this study, simulated epidemics were run 100 times for each FMD-control strategy and results were summarized with respect to the number of FMD-infected, depopulated, and vaccinated farms and animals, and the duration of the FMD epidemic.

5.2.5 Sensitivity analysis

There is uncertainty in model parameters because information used to determine input values was unavailable. Thus the sensitivity of the simulation results to changes of FMD-control parameter values was investigated to determine which parameters in the model most influenced the cost-effectiveness of FMD-control strategies. Control parameters examined here were surveillance detection probability, probability of movement restriction compliance, and the farm depopulation resource constraint. For each sensitivity analysis, the input value for each parameter was altered while leaving the remaining values at the baseline level.

5.3 Results

5.3.1 Cost-effectiveness analysis

According to the FMD epidemic simulation results, the FMD-control strategies with the 0.5 and one kilometre slaughtering strategies and 30 day stop movement strategy did not control FMD spread within the 100 day simulation period (Table 5.6). Therefore, these three strategies were excluded in CE and sensitivity analyses.

The estimated median cost for the simulated baseline strategy was USD 99.7 million (Table 5.7). The simulated median costs were USD 107.6 (range 87.1–126.0) million for the five kilometres slaughtering strategy and USD 168.8 (range 158.5–179.3) million for 60 day stop movement, respectively. The simulated median cost for the ring vaccination strategy was USD 81.1 (range 70.5–114.0) million. Except for the ring vaccination strategy, the simulated median costs of all other alternative FMD-control strategies were larger than the simulated median cost of the baseline strategy.

The probability that the cost of alternative FMD-control strategies was less than the baseline cost (USD 99.7 million) differed among alternative FMD-control strategies. The probability that the simulated cost of the ring vaccination strategy was less than the baseline cost was over 70% (Figure 5.1), whereas the simulated cost of the 60 day stop movement strategy was never less than baseline. FMD-control strategies with a five kilometre radius of pre-emptive slaughtering area showed about a 10% chance of costing less than the baseline cost.

Of the simulated median cost for the baseline strategy (USD 99.7 million), USD 89.3 million was for compensation for animal losses due to culling, USD 9.5 million for carcass disposal, USD 0.4 million for movement restriction, and USD 0.5 million for vaccinating FMD-susceptible animals (Table 5.8). Likewise, compensation for animal loss due to culling accounted for more than 85% of alternative FMD-control strategies costs. Compensation costs were USD 95.8 million for the five kilometre slaughtering strategy, USD 150.8 million for the 60 day stop movement strategy, and USD 71.8 million for the ring vaccination strategy.

5.3.2 Sensitivity analysis

The simulated cost of FMD-control strategies decreased as the number of farms that could be depopulated per day increased. Thus, if the number of depopulated farms per day was increased from

20 to 50, the simulated median cost decreased by USD 13.3 million in the five kilometre slaughtering strategy, by USD 34.4 million in the 60 day stop movement strategy, and by USD 26.6 million in the ring vaccination strategy (Table 5.9). Increasing the detection probability for passive surveillance or the success probability for movement restriction in early phase could also decrease the cost of alternative FMD-control strategies. If the detection probability for passive surveillance was increased from 50% to 90%, the median cost of the 60 day stop movement strategy decreased by USD 31.2 million, from USD 168.8 to 137.6 million. Similarly, if the success probability of movement restriction in the early phase was increased from 70% to 90%, the median cost of the 60 day stop movement strategy decreased by USD 30.1 million, from USD 168.8 to 138.7 million (Table 5.9).

5.4 Discussion

The current study evaluated the cost-effectiveness of FMD-control strategies using a simulation model fitted to the 2010/11 FMD epidemic in the city of Andong, Republic of Korea. According to the evaluation, the most cost-efficient of the alternative strategies was that which applied a ring vaccination in a band from three to five kilometres around FMD-infected farms, a three kilometre area of pre-emptive slaughtering, and 100 days of movement restriction.

The cost information for the study was based on the response to the 2010/11 FMD outbreak in the Republic of Korea (MOSPA, 2011), which may be different for other countries. For example, the labour cost for carcass disposal was USD 1775 per disposal area in the study; however, Bates et al. (2003a) assigned a labour cost of USD 4500 for disposal and disinfection per farm for farms of 884 cattle in California. Based on this, it is clearly not advisable to apply estimates from the current study to other countries. However, the description of cost-effectiveness analysis in the study provides a rational approach that can be used in other countries and for other diseases to evaluate the financial consequences of disease control strategies using an epidemiologic model.

In the study, the amount of financial loss caused by the FMD outbreak was larger in pig farms than in cattle farms in terms of number of FMD-infected animals. The mean number of animals per farm was 1167 for pigs and 20 for cattle, respectively. Results of the study may be applied to other provinces in the Republic of Korea because the mean number of animals was 1020 and 17 for pig and cattle farms, respectively (KOSTAT, 2011). No dairy farms were considered in the model because there were only six farms in the outbreak area. The loss from depopulating dairy farms may be a major financial issue in areas where dairy farms are more common, because the compensation paid for dairy cattle is greater than that paid for beef cattle and, generally speaking, dairy farms are larger. Bates et al. (2003a) estimated the compensation cost for a dairy farm with 884 cows as approximately USD

2 million in California. Thus, the financial consequences of FMD-control strategies might be expected to differ where the distribution of FMD-susceptible farms differs.

A decrease in the period of movement restriction from 100 days (which was applied during the actual FMD epidemic) to 60 days increased the costs of FMD-control strategies. Decreasing the duration of movement restriction in the simulation increased the number of FMD-infected farms, resulting in increased compensation costs for culled animals due to FMD-infection. Despite the financial effectiveness, a long period of movement restriction, which stops every movement in and out of a disease infected area, may face public resistance. During the 2001 FMD epidemic in the United Kingdom, public concern about the welfare of FMD-infected animals no doubt occurred as a result of pictures showing animals in FMD-infected areas starving because feed movement was prohibited (Crispin et al., 2002). Thus, applying a long period of movement restriction should also consider social issues and the social implications of this strategy.

Increasing the radius of the pre-emptive slaughtering area from three kilometres (which was applied during the 2010/11 FMD epidemic) to five kilometres increased the cost of FMD-control strategies. The larger pre-emptive slaughtering area required more resources for slaughtering, such as equipment and labour. Moreover, mass culling of apparently healthy animals may be criticized by the public for its cruelty or lack of perceived necessity. During the 2001 FMD epidemic in the Netherlands, farmers initially resisted depopulation, resulting in a delay in applying FMD-control measures (Pluimers et al., 2002). Thus, when decision makers opt to implement pre-emptive slaughtering over a large area to prevent the spread of FMD, consideration needs to be given to social as well as economic issues; otherwise the control program may be delayed.

Increasing the number of farms that could be depopulated each day reduced the cost of FMD-control strategies, mainly because the total number of FMD-infected farms was reduced by removing susceptible animals. Given the impact on total cost, thought should be given to how to increase the capability for depopulating farms. One way to increase this would be to make a centralized slaughtering facility within the infected area (Pluimers et al., 2002). Compared to slaughtering animals at several locations, centralising slaughtering facilities will reduce the resources required to depopulate a farm, allowing more farms to be depopulated each day.

The cost of FMD-control strategies in the study was estimated based on direct costs of the FMD epidemic, such as compensation for culled animals or applying costs for control measures. If indirect costs, such as decreased domestic animal product consumption, tourism, or a ban on exporting animals and animal products, are included in the estimation, the cost of FMD-control strategies will increase. Thompson et al. (2002) estimated the indirect cost of the 2001 FMD epidemic in the United Kingdom. In their study, the loss to the tourism industry (businesses associated with tourism) was GBP 2.7–3.2 billion. It is not straightforward to quantify the indirect cost of FMD epidemic because an FMD epidemic would influence various industries including tourism and agricultural businesses. An economic analysis technique such as input-output analysis or a general equilibrium model is needed to estimate the indirect losses of FMD epidemic (Thompson et al., 2002).

5.5 Conclusion

The results of this study show that an FMD-control strategy comprising a pre-emptive slaughtering area with a radius of three kilometres, 100 days of movement restriction, and a ring vaccination in a band from three to five kilometres around a farm, is the most cost-efficient among the alternative strategies examined here. Decreasing the duration of movement restriction increased the cost because the simulated number of FMD-infected farms increased. Extending the radius of the pre-emptive slaughtering area increased both the number of animals that were slaughtered and the cost, because the required resources such as equipment and labour increased. In addition to cost-effectiveness, epidemiologic and social effectiveness of FMD-control strategies should be considered before choosing a FMD-control strategy.

Table 5.1. Details of baseline and alternative control strategies for foot-and-mouth disease (FMD) control in the city of Andong, Republic of Korea, 2010-2011.

Strategy	Values of control measures		
	Radius of pre-emptive slaughtering (kilometres)	Duration of movement restriction (days)	Application of vaccination
Baseline	3	100	Blanket*
Alternatives			
Different radius of pre-emptive slaughtering			
0.5 kilometre	0.5	100	Blanket
1 kilometre	1	100	Blanket
5 kilometre	5	100	Blanket
Different duration of movement restriction			
30 day	3	30	Blanket
60 day	3	60	Blanket
Application of ring vaccination			
Ring vaccination	3	100	Ring #

* Vaccinating all FMD-susceptible animals in the study area.

Vaccinating all FMD-susceptible animals in a band from three to five kilometres around an FMD-infected farm.

Table 5.2. Estimated costs of compensation for cattle and pig farms depopulated due to foot-and-mouth disease (FMD) infection or pre-emptive slaughtering in the city of Andong, Republic of Korea, 2010-2011.

Description	Value per head (USD)	Mean no. of head*	Total cost (USD)
Cattle farm			
Beef cattle (male, > 600 kilogram)	4,140	3	12,420
(female, > 600 kilogram)	3,767	5	18,835
(male, ≥ 350 – 600 kilogram)	2,043	5	10,215
(female, ≥ 350 – 600 kilogram)	4,030	3	12,090
Beef calf (male, < 350 kilogram)	1,779	3	5,337
(female, < 350 kilogram)	1,688	1	1,688
Subtotal		20	60,585
Pig farm			
Farrowing pig	71	244	17,324
Weaning pig	110	389	42,790
Growing/finishing pig	260	498	129,480
Adult	900	36	32,400
Subtotal		1,167	221,994

Source: National Statistics on livestock price, Statistics Korea, 2010.

*Mean values were based on the National Statistics calculations for the number of animals per farm.

Table 5.3. Estimated management cost per disposal area* of slaughtered animals in the city of Andong, Republic of Korea.

Item	Value per unit (USD)	Units	Total cost (USD)
Excavator rent fee per day	400	15	6,000
Septic tank lorry	58	2	116
Sawdust per cubic metre	33	18	594
Deodorant per litre	21	24	504
Fermentor per litre	5	15	75
Disinfectant per kilogram	7	30	210
Waterproof film per roll	63	1	63
Calcium oxide per kilogram	1	60	60
Signboard	83	1	83
Sprayer	100	1	100
Personal protective gear	21	3	63
Labour cost per man	355	5	1,775
Total			9,643

* One disposal area covered two beef farms or one third of a pig farm.

Source: Ministry of Security and Public Administration, White Paper: Reactions to Foot-and-Mouth Disease in 2010/11.

Table 5.4. Estimated management cost for running one control office for 100 days to restrict the movement of animals and animal products during the foot-and-mouth disease (FMD) epidemic in the city of Andong, Republic of Korea, 2010-11.

Item	Value per unit (USD)	Units	Total cost (USD)
Labour cost per day	150	100	15,000
Transportation rental per day	25	100	2,500
Fuel cost per day	21	100	2,100
Food cost per day	19	100	1,900
Water tank	125	1	125
Sprayer	100	1	100
Protective gear	21	3	63
Disinfectants per kilogram	7	30	210
Signboard	83	1	83
Total			22,081

Source: Ministry of Security and Public Administration, White Paper: Reactions to Foot-and-Mouth Disease in 2010/11.

Table 5.5. Estimated cost for applying blanket vaccination to control foot-and-mouth disease (FMD) in the city of Andong, Republic of Korea, 2010-11.

Item	Value per unit (USD)	Unit	Total cost (USD)
Administration			
Labour cost per person*	1,750	30	52,500
Food cost per person*	88	30	2,640
Transportation rent fee per unit*	175	10	1,750
Fuel cost per unit*	146	10	1,460
Protective gear per person*	21	30	630
Disinfectants per kilogram*	7	30	210
Subtotal			59,190
Vaccine			
Vaccine per head of cattle	4	1	4
Vaccine per head of pig	4	1	4

*all costs were estimated for a 7 day period.

Source: Ministry of Security and Public Administration, White Paper: Reactions to Foot-and-Mouth Disease in 2010/11.

Table 5.6. Predicted foot-and-mouth disease (FMD) epidemic duration for different radius of pre-emptive slaughtering area, duration of movement restriction, and application of ring vaccination for FMD-control strategies to control the 2010/11 FMD outbreak in the city of Andong, Republic of Korea.

	Duration of FMD epidemics (days)				
	Min	Q1	Med	Q3	Max
Radius of pre-emptive slaughtering (kilometre)					
0.5	100+	100+	100+	100+	100+
1	99	100+	100+	100+	100+
3*	49	62	77	93	100+
5	49	56	75	80	99
Duration of movement restriction (days)					
30	98	100+	100+	100+	100+
60	95	96	98	99	100+
100*	49	62	77	93	100+
Application of vaccination					
Ring vaccination#	51	65	79	95	100+
Suppressive vaccination*	49	62	77	93	100+

Min: minimum number of simulation result, Q1: 25th percentile of simulation result, Med: median number of simulation result, Q3: 75th percentile of simulation result and Max: maximum number of simulation result.

+ Note, values of 100 indicate the epidemic was not controlled by the end of the simulation runs.

* Baseline FMD-control strategy.

Vaccinating all FMD-susceptible animals in a band from three to five kilometres around FMD-infected farms.

Table 5.7. Simulated costs (USD million) for baseline and alternative foot-and-mouth disease (FMD) control strategies in the city of Andong, Republic of Korea.

Strategy#	Minimum	25th percentile	Median	75th percentile	Maximum
Baseline*	N/A	N/A	99.7	N/A	N/A
5 kilometre slaughtering	87.1	101.7	107.6	119.2	126.0
60 day stop movement	158.5	165.4	168.8	171.7	179.3
Ring vaccination	70.5	76.1	81.1	94.6	114.0

* The cost of baseline FMD-control strategy was estimated based on the 2010/11 FMD epidemic in the study area.

0.5 kilometre and one kilometre slaughtering strategies and 30 day stop movement strategy were excluded because they did not control FMD spread in the simulation.

Table 5.8. Details for the median costs (USD million) for baseline and alternative foot-and-mouth disease (FMD) control strategies in the city of Andong, Republic of Korea, 2010-2011.

Strategy#	Compensation	Slaughtering	Movement restriction	Vaccination
Baseline	89.3	9.5	0.4	0.5
5 kilometre slaughtering	95.8	10.9	0.4	0.5
60 day stop movement	150.8	17.0	0.4	0.6
Ring vaccination	71.8	8.6	0.4	0.3

0.5 and one kilometre slaughtering strategies and 30 day stop movement strategy were excluded because they did not control FMD spread in the simulation.

Table 5.9. Sensitivity analysis of the detection probability of passive surveillance, the success probability of early movement restriction, and the number of farms that could be depopulated per day, expressed as expected median costs (USD million) for foot-and-mouth disease (FMD) control strategies in the city of Andong, Republic of Korea, 2010-11.

Parameter	5 kilometres slaughtering	60 day stop movement	Ring vaccination
Resources constrained for depopulating farms (number of farms per day)			
10	147.5	175.2	98.2
20*	107.6	168.8	81.1
30	101.1	151.4	64.9
40	98.7	144.8	59.5
50	94.3	134.4	54.5
Detection probability of passive surveillance (%)			
10	123.4	183.6	98.3
30	120.1	172.3	89.4
50*	107.6	168.8	81.1
70	103.3	154.1	66.7
90	98.7	137.6	65.4
Success probability of movement restriction in early phase (%)			
10	133.6	193.6	110.5
30	126.7	182.8	97.3
50	121.1	175.3	84.5
70*	107.6	168.8	81.1
90	103.2	138.7	67.2

* default input value.

0.5 and one kilometre slaughtering strategies and 30 day stop movement strategy were excluded because they did not control FMD spread in the simulation.

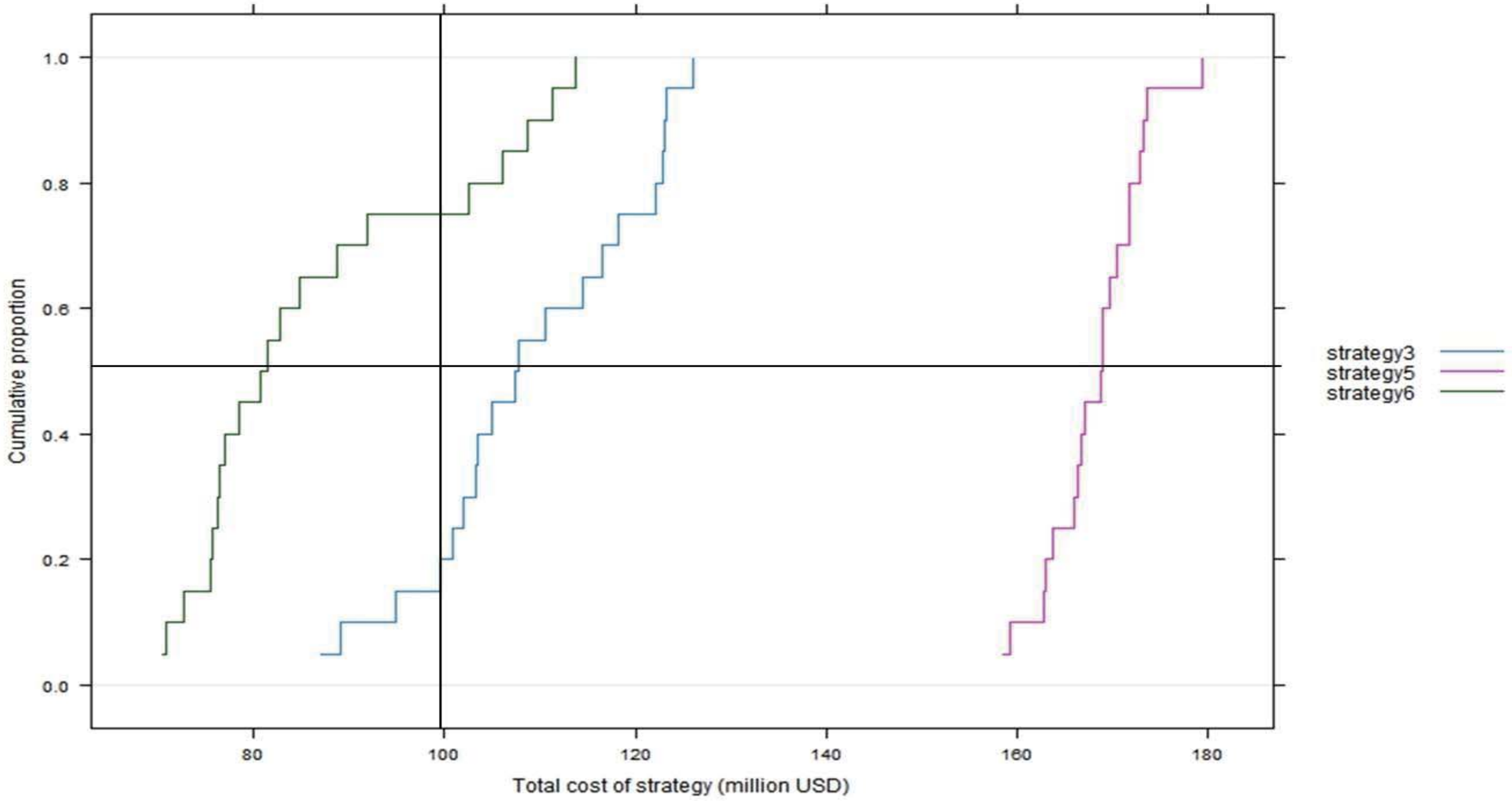

Figure 5.1. Simulated cumulative distributions of alternative FMD-control strategies. The vertical solid line indicates the cost of the baseline FMD-control strategy (USD 99.7 million) and the horizontal solid line indicates a cumulative proportion of 50%. Strategy 3: five kilometre slaughtering, strategy 5: 60 day stop movement, strategy 6: ring vaccination. The 0.5 and one kilometre slaughtering strategies and 30 day stop movement strategy were excluded because they did not control FMD spread in the simulation.

Chapter VI

6 Multi-criteria decision analysis (MCDA) to evaluate foot-and-mouth disease (FMD) control strategies from the perspectives of chief veterinary officers in the Asia-Oceania region

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Abstract

The objective of this study was to evaluate the effectiveness of foot-and-mouth disease (FMD) control strategies using a multi-criteria decision analysis (MCDA). The FMD-control strategies were evaluated against epidemiologic, economic, and social-environmental criteria, accounting for the preferences of chief veterinary officers (CVOs) from the Asia-Oceania region, with preferences quantified using a questionnaire study. Previously reported simulation results of an FMD outbreak were used to measure the epidemiologic effectiveness of FMD-control strategies. The simulated FMD outbreak results, such as number infected farms, duration of the outbreak, and size of the outbreak area were compared for alternative FMD-control strategies. Based on previous simulation and economic modelling results, and incorporating a literature search to quantify the social and environmental outcomes of an FMD outbreak, an MCDA analysis was conducted to evaluate control strategies. According to the MCDA results, the most preferred FMD-control strategy, with the highest overall score of 57.20, consisted of pre-emptive slaughtering within a three kilometre radius, 100 days of movement restriction, and vaccinating all FMD-susceptible animals in a band from three to five kilometres around FMD-infected farms. In contrast, the FMD-control strategy with the same area of pre-emptive slaughtering and vaccination strategy but with 30 days of movement restriction was the least preferred, with the lowest overall score of 32.42. The evaluation of the FMD-control strategies presented here, using MCDA, provides scientific evidence for selecting the baseline strategy as the most preferred FMD-control strategy among those examined, based on the epidemiologic and non-epidemiologic preferences of CVOs in the Asia-Oceania region.

6.1 Introduction

Foot-and-mouth disease (FMD) remains one of the most important diseases in the livestock industry (OIE, 2013b). In an outbreak, FMD can spread rapidly between susceptible animals; therefore, rapid implementation of control strategies is of critical importance. One way to ensure control strategies are implemented quickly is to gain the support of stakeholders, and to achieve this, decision makers should engage with stakeholders and consider communication options prior to an outbreak (Rweyemamu and Astudillo, 2002). Failure to rapidly implement control strategies due to communication failure was highlighted during the 2001 FMD epidemic in the Netherlands, where the government spent considerable time convincing farmers to adopt a pre-emptive slaughtering strategy (Pluimers et al., 2002) and the control of FMD was therefore delayed.

In order to allow rapid deployment of controls, decisions regarding control strategies need to be in place prior to an outbreak. Decision analysis may be used to organize the different views of stakeholders in a rational and scientific manner and enable the effective communication of these decisions. One tool to support communication and transparently show trade-offs is multi-criteria decision analysis (MCDA). MCDA provides a systematic methodology to combine information about a problem with solutions and with stakeholders' views to solve decision making problems. MCDA has been used in multiple fields, including ecology (Mendoza and Martins, 2006), engineering (Laken, 2007), and environmental science (Hajkowicz and Collins, 2007). MCDA is an emerging methodology in veterinary science and is applicable to support decisions about control strategies for infectious diseases. Mourtis et al. (2011) applied MCDA to evaluate control strategies for classical swine fever (CSF), focusing on the views of chief veterinary officers (CVOs) from France, Germany, Great Britain, Hungary, Italy, and Poland. Cox et al. (2013) applied MCDA to prioritise infectious diseases, based on control strategies and the likelihood of emergence associated with climate change, with the preferences of academic experts and government officers in Canada. Brookes et al. (2014a) applied MCDA, using the preference of Australian pig producers, to prioritise exotic diseases for the pig industry in Australia.

To be successful, decisions regarding FMD control strategies must rely on solid scientific evidence. The objective of this study was to describe an MCDA process for supporting decisions about FMD control strategies, using the perspectives of different stakeholders. The stakeholders investigated were the CVOs from the Asia-Oceania region.

6.2 Materials and methods

6.2.1 Overview (background and general framework)

Decisions regarding control strategies for infectious animal diseases such as FMD are suitable for assessment using MCDA. Stakeholders can compare the effectiveness of FMD-control strategies by breaking the problem into several criteria. The effectiveness of FMD-control strategies, such as movement restriction, vaccination, or slaughtering FMD-infected animals, varies depending on whether and when strategies are applied. Using simulation modelling, Bates et al. (2003b) reported that pre-emptive slaughtering of susceptible animals to control FMD spread would be more effective than vaccination or movement restriction. If pre-emptive slaughtering were applied as an additional FMD control measure to the US mandated FMD strategy (slaughter of FMD-infected farm, closure of saleyards within 10 kilometres of an FMD-infected farm, and surveillance within 20 kilometres of an FMD-infected farm), the duration of the outbreak was shorter and the number of infected farms was lower than if vaccination or movement restriction were used as control strategies. However, from an economic perspective, pre-emptive slaughtering was more costly than either vaccination or movement restriction. Consequently, stakeholders need a method to compare the effectiveness of FMD-control strategies using multiple criteria in a scientific manner.

MCDA assists with decision making by systematically analysing a problem. The problem is broken into manageable pieces (criteria) and alternative options for solving the problem are evaluated for each criterion. In an MCDA for disease control strategies, the evaluation could be based on the results of the epidemiologic, economic, and social-environmental effectiveness of control strategies. The effectiveness of disease control strategies across criteria is expressed as numerical values and can be synthesized to a single score to estimate the overall effectiveness. The control strategies are then ranked according to their overall effectiveness. MCDA methodology used in the current study follows the eight steps described by Mouritis et al (2011): 1) determining the decision making context, 2) identifying alternatives to be appraised, 3) determining the criteria, 4) measuring the criteria, 5) standardising the measurement, 6) determining criteria weight, 7) calculating overall scores and rankings, and 8) performing a sensitivity analysis.

6.2.2 Determining the decision making context (Step 1)

This study focused on evaluating the effectiveness of FMD-control strategies with multiple success criteria. In previous studies, FMD-control strategies have been evaluated with an epidemiologic criterion (Bates et al., 2003b; Yoon et al., 2006), an economic criterion (Thompson et al., 2002; Bates et al., 2003a) and a social criterion (Cohen et al., 2007). MCDA has not been used to evaluate FMD-control strategies in countries in the Asia-Oceania region, where some countries are FMD-free and others have endemic FMD. The current study incorporated the approaches taken by previous studies [Chapter 4] and quantified the overall effectiveness of FMD-control strategies using stakeholder preferences. In other words, the current study applies MCDA to decision making for a specific scenario which was based on the 2010/11 FMD outbreak in the city of Andong, Republic of Korea. The stakeholders in the study were CVOs from the Asia-Oceania region because they are either the final decision makers or they are relied upon by decision makers when selecting an FMD-control strategy. Epidemiologic and economic information related to FMD-control strategies was obtained from the 2010/11 FMD outbreak in the Republic of Korea (MOSPA, 2011) and social-environmental information about the FMD outbreak was obtained from the literature review.

6.2.3 Identifying alternatives to be appraised (Step 2)

The baseline FMD-control strategy was based on the FMD-control strategy implemented during the 2010/11 FMD outbreak in the Republic of Korea (MOSPA, 2011). The baseline strategy applied pre-emptive slaughtering within a three kilometre radius of an infected farm, 100 days of movement restriction, and vaccination of all FMD-susceptible animals. This baseline control strategy was altered to create alternative FMD-control strategies. Alterations were: 1) pre-emptive slaughtering within a radius of 0.5, one and five kilometres of an infected farm; 2) movement restriction durations of 30 and 60 days; and 3) ring vaccination in a band from three to five kilometres around FMD-infected farms (Table 6.1).

6.2.4 Determining the criteria (Step 3)

The impact of FMD-control strategies is related to epidemiologic, economic, and social-environmental issues (Huirne et al., 2005; Mourits et al., 2010); so these three criteria were applied in the current study. First, the epidemiologic criterion was used to evaluate the effectiveness of FMD strategies in eradicating or controlling the outbreak. The duration of the FMD outbreak, size of FMD-infected area, number of FMD-infected farms and animals, and number of depopulated farms and animals were included in the epidemiologic criterion. Second, the economic criterion identified the impact of an FMD control strategy on the economic performance of the farm, industry, or country.

The operating cost of FMD-control strategies, farm loss from the number of depopulated animals, farm loss from movement restrictions, industry loss from movement restrictions, loss from export bans, and loss from a decrease in tourism were included in the economic criterion. Finally, the social-environmental criterion indicated the impact of FMD control strategies on social and environmental issues. The mental health of the public and of farmers with FMD-affected farms, the welfare of FMD-infected and non-infected animals, and air and ground pollution from carcass disposal were included in the social-environmental criterion.

6.2.5 Measuring the criteria (Step 4)

A simulation model was constructed to measure the epidemiologic criterion for each FMD-control strategy. A state-transition simulation software application, InterSpread Plus (EpiCentre, Massey University, New Zealand), was used to simulate the FMD outbreak for each strategy. This has previously been used to simulate the spread of FMD between farms in the Republic of Korea (Yoon et al., 2006) and in the United Kingdom (Morris et al., 2001; Thompson et al., 2002). Simulated outcomes were the number of animals and farms that were infected, detected, slaughtered, and vaccinated during the simulated FMD outbreak, and the duration of the disease outbreak. The median value was used as a measure of effectiveness for FMD-control strategies in the epidemiologic criterion. Further information regarding the epidemiologic modelling and the development of the epidemiologic criterion can be found in [Chapter 4].

To measure the economic criterion, a deterministic economic spreadsheet model was developed from the outcomes of the simulation model. These results have been calculated elsewhere [Chapter 5], but briefly, the total farm losses due to the slaughtering of infected animals were estimated using the total number of slaughtered animals, as determined by the epidemiologic model, multiplied by the compensation cost per animal. Similarly, economic losses from an export ban were estimated using the duration of FMD outbreak, as determined by the epidemiologic model, multiplied by the economic loss per day. Costs associated with FMD-control strategies and economic losses due to an FMD outbreak were obtained from the 2010/11 FMD outbreak in the Republic of Korea (MOSPA, 2011).

The social-environmental criterion was measured based on a literature review combined with the FMD outbreak results from the epidemiologic model. The mental health of the public and of farmers with FMD-affected farms, the welfare of FMD-infected and non-infected animals, and air and ground pollution from carcass disposal were included in the social-environmental criterion. The mental health of farmers was quantified by relating the mental health of farmers with FMD-affected farms to the number of slaughtered farms. Van Haaften et al. (2004) used a survey to determine the mental health status of 661 dairy farmers after the 2001 FMD outbreak in the Netherlands; they found farmers experienced ‘post-traumatic stress at levels requiring professional help’ (Van Haaften et al., 2004, page 346). Similarly, Mort et al. (2005) surveyed the mental health of 54 people in North Cumbria, the outbreak area during the 2001 FMD outbreak in the United Kingdom. Those people experienced mental health problems such as depression or stress. In the current study, the mental health of farmers with FMD-affected farms, and of the public, will worsen as the simulated number of depopulated farms increases in the epidemiologic model. Crispin et al. (2002) described animal welfare issues related with FMD control during the 2001 FMD outbreak in the United Kingdom. The study identified that improper or inappropriate slaughter methods were applied during the outbreak because a great many animals had to be culled and slaughtering had to be applied as early as possible to minimise the FMD spread. If the simulated number of depopulated animals increases then animal welfare is likely to worsen. The environmental criterion can be measured by experimental studies that quantify the contaminants resulting from carcass disposal. Yuan et al. (2013) examined contaminants in discharges from buried carcasses. In their study, residues such as veterinary antimicrobials or monensin could potentially contaminate the soil near the burial area. Similarly, the Cumbria FMD panel (Cumbria Foot and Mouth Disease Inquiry Panel., 2002) reported that emissions from pyres for carcass disposal caused increased levels of sulphur dioxide, nitrogen oxides, and dioxins. The current study shows that if the simulated number of depopulated farms is increased then air and ground pollution due to carcass disposal will worsen.

6.2.6 Standardising the measurement (Step 5)

Standardization, the transformation of raw measurements into one common measurement unit, was applied so that measurements using different scales were comparable. The measurement scales of each criterion differed. For example, epidemiologic units, such as the number of FMD-infected farms or the duration of FMD outbreak, were used to measure the effectiveness of FMD-control strategies in the epidemiologic criterion; however, in the economic criterion, economic loss due to an FMD outbreak was measured as monetary units. Thus, a maximum score procedure was applied: the measurement of outcomes for each criterion was divided by the highest measurement of the criterion (Equation 6.1) in each group (i.e., epidemiologic, economic and social-environmental).

$$x'_i = x_i \; / \; x_i^{max} \quad \text{(Equation 6.1)}$$

Where x'_i : standardized score of alternative for the *i*th indicator; x_i : measurement of alternative for the *i*th indicator, x_i^{max} : maximum measurement of alternative for the *i*th indicator

As a result, the scores were transformed so they ranged from zero to one, where zero indicates the lowest adverse outcome and one the highest. The standardized score was then deducted from one, to ensure that the FMD-control strategy with the highest score indicated the preferred strategy.

6.2.7 Determining criteria weight (Step 6)

A questionnaire was designed to measure the importance of the criteria for each FMD control strategy, accounting for the perspectives of CVOs. The importance of the criteria and indicators was quantified to weight the criteria and indicators. The questionnaire quantified the relative importance of epidemiologic, economic, and social-environmental criteria associated with FMD-control outcomes. The scale of scores was defined from 0 to 100: the higher the score the more important the criterion. This study has been reported previously in Chapter 3, but, briefly, during the 28th conference of the OIE Regional Commission for Asia, the Far East and Oceania (Cebu, Philippines, 18-22 November 2013), 21 CVOs or their representatives from the Asia-Oceania region completed the survey anonymously (Table 6.2). Questionnaire responses were collected on 19 November 2013 and the response rate was 100%. The median scores of the relative importance of indicators were used as weights; for example, the weighted score for the size of FMD outbreak area was calculated as the standardized score (as described above) multiplied by the median score of relative importance for the size of FMD outbreak area.

6.2.8 Calculating overall scores and rankings (Step 7)

The weighted score of outcomes for each indicator was calculated as the standardized score multiplied by the weight of the indicator. The overall score of outcomes within each criterion (epidemiologic, economic, or social-environmental) was calculated by dividing the sum of the weighted scores by the number of outcomes in the criterion (Equation.6.2). For example, if the number of epidemiologic outcomes was six, the overall score of the FMD-control strategy for the epidemiologic criterion was the sum of six weighted scores divided by six.

$V = \sum_{i=1}^{n}(w_i c_i / n)$ (Equation.6.2)

where V is the overall score of alternative, w_i: the weight for the i^{th} indicator, c_i is the standardized score of the alternative for the i^{th} indicator and n is the number of indicators.

The overall score of FMD-control strategies for each criterion was multiplied by the weight of the criterion to take into account the importance of the criteria. The FMD-control strategies were ranked according to their weighted overall score, which was the sum of the weighted overall scores of three criteria: epidemiologic, economic, and social-environmental. A sum of weighted scores was appropriate for the current study because each criterion score was transformed and standardized.

6.2.9 Performing a sensitivity analysis (Step 8)

The overall scores of FMD-control strategies were based on the median value of simulation outcomes, which would reflect a decision made by a risk neutral individual. A sensitivity analysis was performed to assess the impact of changing the simulation outcome values on the overall score of FMD-control strategies. The 5th and 95th percentile values of simulation outcomes, reflecting risk taking and risk adverse individuals, were used to calculate the score of FMD-control strategies. For example, all 5th percentile values of simulation outcomes were used to calculate the scores of FMD-control strategies for epidemiologic, economic, and social-environmental criteria for risk taking individuals. The rankings of FMD-control strategies for risk adverse individuals were calculated in the same way, using the 95th percentile values of simulation outcomes. The rankings of FMD-control strategies for the epidemiologic, economic, and social-environmental criteria with 5th and 95th percentile values were compared with the median value of simulation results.

6.3 Results

6.3.1 Weights of criteria

The weighted scores for the epidemiologic, economic, and social-environmental indicators are shown in Table 6.3. Indicators with the highest weighted scores were the size of FMD outbreak area (90, range 45–100) in the epidemiologic criterion, the cost of FMD-control measures (80, range 10–100) in the economic criterion, and mental health of affected farmers (60, range 10–100) in the social-environmental criterion.

6.3.2 Scores of FMD-control strategies

In the epidemiologic criterion, the strategy with a slaughtering area of radius five kilometres had the highest weighted score for the outcome of the area of the FMD outbreak (Table 6.4). The baseline strategy was the highest scoring strategy for the outcome of the size of FMD outbreak area. Baseline strategy, 60 day stop movement, and ring vaccination were the strategies with the highest weighted scores for duration of FMD outbreak. The strategy with the highest weighted score for the outcomes of number of FMD-infected farms and animals was slaughtering within a five kilometre radius. The strategy with a 0.5 kilometre slaughtering area had the highest scores for the outcomes of the number of depopulated farms and animals.

In the economic criterion, baseline strategy and ring vaccination were the control strategies with the highest weighted scores for the outcomes of cost of control measures, farm loss from depopulation, export loss, and tourism loss, along with 60 day stop movement for the latter two indicators. Thirty day stop movement was the control strategy with the highest weighted score for the outcomes of farm and industry losses resulting from movement restriction (Table 6.5).

In the social-environmental criterion, the FMD-control strategy with the highest weighted score was the 0.5 kilometre slaughtering strategy for the outcomes of mental health of affected farmers, welfare of non-infected animals, air pollution, and ground pollution. The control strategy with the highest weighted score for the outcomes of mental health of the public and welfare of infected animals was slaughtering within a five kilometre radius (Table 6.6).

6.3.3 Overall scores and rankings of FMD-control strategies

Under the epidemiologic criterion, baseline strategy, five kilometre slaughtering, 60 day stop movement, and ring vaccination scored highly, with overall scores of 22.38, 22.10, 22.04, and 21.69, respectively (Table 6.7). In contrast, 0.5 and one kilometre slaughtering and 30 day stop movement scored low, with overall scores of 8.28, 10.04 and 10.58, respectively. Under the economic criterion, baseline strategy, 30 and 60 day stop movement, and ring vaccination scored high with overall scores of 15.74, 15.52, 14.92 and 14.38, respectively, but 0.5, one and five kilometre slaughtering scored low with overall scores of 7.66, 8.24 and 11.99, respectively. For the social-environmental criterion, one and 0.5 kilometre slaughtering, ring vaccination, baseline strategy and 60 day stop movement scored highly, with overall scores of 27.59, 26.38, 24.27, 24.06 and 23.91, respectively, and only the five kilometre slaughtering and 30 day stop movement scored low, with overall scores of 16.64 and 9.32, respectively. In total, the rankings of FMD-control strategies in decreasing order were ring vaccination, baseline strategy, 60 day stop movement, five kilometre slaughtering, one kilometre slaughtering, 0.5 kilometre slaughtering, and 30 day stop movement.

6.3.4 Sensitivity analysis

When the 5th percentile of simulation results was used, the most preferred FMD-control strategies were the baseline strategy for the epidemiologic and social-environmental criteria and the 60 day stop movement strategy for the economic criterion. When the 95th percentile of simulation results was applied, the most preferred FMD-control strategies were baseline strategy for the epidemiologic criterion and 30 day stop movement strategy for the economic criterion and the social-environmental criterion (Table 6.8).

6.4 Discussion

MCDA was applied to evaluate the effectiveness of FMD-control strategies based on the preference of stakeholders; namely, CVOs from the Asia-Oceania region. Alternative FMD-control strategies were designed based on the actual FMD-control strategy applied during the 2010/11 FMD outbreak in the Republic of Korea. Three criteria were used to assess alternative control strategies: epidemiologic, economic, and social-environmental, based on previous studies (Mourits et al., 2010). From these criteria, the ring vaccination strategy, which applied pre-emptive slaughtering within a three kilometre radius of an FMD-infected farm, 100 days of movement restriction, and vaccinating all FMD-susceptible animals in a band from three to five kilometres around FMD-infected farms, was the most preferred FMD-control strategy. The evaluation of FMD-control strategies using an MCDA can provide a scientific evidence for selecting an appropriate FMD-control strategy.

A sensitivity analysis of the MCDA was performed to examine the extent to which rankings would differ among CVOs' different risk attitudes — risk taking, neutral, or adverse, based on the simulated outcome of the number of FMD-infected farms. If CVOs are risk taking, they may assume the 5th percentile of simulated FMD-infected farms will occur for a selected control strategy and then the preferred FMD-control strategy would be the baseline strategy with stop movement reduced from 100 to 60 days. An advantage of a 60 day stop movement strategy is that due to its reduced duration it will require fewer resources, such as the labour or equipment needed to apply movement restriction. The trade-off for implementing the 60 day stop movement strategy is a possible increase in the outbreak area size. If we take the 50th percentile (median) to represent values that a risk neutral CVO would select for decision making purposes, then the preferred option would be the ring vaccination strategy. If, on the other hand, the CVOs were risk averse, they may have focused on the 95th percentile of simulated FMD-infected farms and chosen the baseline strategy. Most CVOs tend to be risk averse and would focus on more negative outcomes, such as the 95th percentile of simulated FMD-infected farms (personal communication with Tim Carpenter, 2015).

The difference in overall score for baseline versus ring vaccination was only 0.05. However, the two scenarios have very different resource requirements because the baseline strategy vaccinates all FMD-susceptible animals in the study area, while ring vaccination is applied only to FMD-susceptible animals in a band from three to five kilometres around FMD-infected farms. The saved resource, such as labour or equipment, can be allocated to other FMD-control measures, such as movement restriction or depopulation. The disadvantage of ring vaccination is that the FMD outbreak area size might be larger than that of the baseline strategy. We found the weighted score for the size of the outbreak area for the baseline strategy was more than three times that for ring vaccination. For stakeholders who consider the size of the outbreak area more important than any other indicator, ring vaccination might not be a recommended alternative.

A systematic process of MCDA, including identifying alternative disease control strategies, measuring the effectiveness of strategies, standardizing the measurements, reflecting stakeholders' preferences, and calculating the overall effectiveness of strategies, can be helpful for evaluating infectious animal disease control strategies around the world. This process can be applied to infectious diseases other than FMD. Mourtis et al. (2011) applied MCDA to evaluate control strategies for classical swine fever (CSF) using the preference of CVOs in Europe. The European study and ours both used the preferences of CVOs as weights for the criteria to evaluate control strategies for infectious livestock diseases. However, the rankings of FMD-control strategies in our study may not be directly applied to other countries because the FMD-control strategies were designed based on the control plan of the Republic of Korea (MOSPA, 2011). In the Korean FMD-control plan pre-emptive slaughtering is compulsory, but in the European Union (EU, 2003), pre-emptive slaughtering of FMD-susceptible animals around FMD-infected farms is not compulsory. Therefore, to determine a preferred control strategy for other countries, alternative control scenarios would need to be examined and a new MCDA would be required.

Generally, CVOs are interested in the epidemiologic effectiveness of control strategies, so control strategies with low epidemiologic efficacy would expect to be less preferred over other FMD-control strategies. The disease status of countries might also be influential in choosing control strategies. Among 21 countries in the study, 12 — Cambodia, China (People's Republic of), Chinese Taipei, Iraq, Japan, Republic of Korea, Mongolia, Russia, Sri Lanka, Thailand, and Vietnam — have experienced an FMD outbreak; therefore, FMD-control strategies with low epidemiologic efficacy, such as 0.5 kilometre slaughtering or 30 day stop movement, were less preferred.

The MCDA methodology can be extended to examine the preferences of other stakeholders like farmers, environmentalists, or the public, as their preferred disease control outcomes might differ. Farmers' preferences among epidemiologic outcomes may differ from those of CVOs; for example, Australian pig farmers focused more on the duration of pig disease than on the case fatality of the disease (Brookes et al., 2014b). Therefore, farmers may prefer a control strategy that can shorten an outbreak, rather than one that reduces the mortality rate. Other stakeholders, such as the public or environmentalists, also have different preferences for livestock disease outcomes. During the FMD outbreak in 2001 in the Netherlands, the public opposed pre-emptive slaughtering due to perceptions about animal welfare (Pluimers et al., 2002). Consequently the public may prefer strategies that do not rely on slaughter strategies. Therefore, the next step of the MCDA methodology used here is to measure the preference of various stakeholders and stakeholders in different regions.

One limitation of the current study was the use of linear aggregation of scores. A linear aggregation of scores to calculate the overall scores of alternatives requires an assumption that the criteria are mutually independent (Clemem and Reilly, 2001). While linear aggregation of scores has been used in previous studies (Mourits et al., 2010; Brookes et al., 2014a), this assumption of independence was violated for some criteria. Thus, the MCDA results presented in the study were interpreted in light of the dependency between criteria. Dependency between criteria indicated that if one FMD-control strategy ranked high in one criterion, then it might be also rank high in another criterion. For example, the low scores of epidemiologic indicators for the one kilometre slaughtering strategy might result in low scores for economic indicators because the larger outbreak increased the cost of control. The degree of dependency between criteria might be quantified by asking stakeholders whether their preferred criteria had been assigned dependently or not; in other words, stakeholders would be asked to explain the reasons for their scores. Active participation of stakeholders for selecting criteria or assigning values for criteria is required to quantify the degree of dependency, but this process was logistically not feasible in the current study because the survey had to be completed within a limited time. Further work is required to quantify the dependency of criteria for CVOs.

6.5 Conclusion

The study applied MCDA to evaluate the effectiveness of FMD-control strategies based on the preferences of CVOs or their representatives from the Asia-Oceania region. The CVOs considered the epidemiologic criterion, in particular the size of FMD outbreak area, more important than economic or social-environmental criteria. The FMD-control strategy comprising a three kilometre radius for pre-emptive slaughtering, 100 days of movement restriction, and vaccinating all FMD-susceptible animals in a band from three to five kilometres around FMD-infected farms had the highest overall score, whereas the strategy with 30 days of movement restriction but the same pre-emptive slaughtering and vaccination area scored the lowest. When the 95th percentile of simulation results was used instead of the median value (default simulation results) to evaluate FMD-control strategies, the FMD-control strategy comprising a three kilometre radius for pre-emptive slaughtering, 100 days of movement restriction, and vaccinating all FMD-susceptible animals had the highest overall score. The evaluation of FMD-control strategies using MCDA can provide scientific evidence for selecting an appropriate FMD-control strategy. In addition, MCDA can be applied to evaluate control strategies for infectious animal diseases other than FMD.

Table 6.1. Details of baseline and alternative control strategies for foot-and-mouth disease (FMD) control strategies.

Strategy	Values of control measures		
	Radius of pre-emptive slaughtering (kilometres)	Duration of movement restriction (days)	Application of vaccination
Baseline	3	100	Blanket*
Alternatives			
Different radius of pre-emptive slaughtering			
	0.5	100	Blanket
	1	100	Blanket
	5	100	Blanket
Different duration of movement restriction			
	3	30	Blanket
	3	60	Blanket
Application of ring vaccination			
Ring vaccination	3	100	Ring#

* Vaccinating all FMD-susceptible animals in the study area.

Vaccinating all FMD-susceptible animals in a band from three to five kilometres around FMD-infected farms.

Table 6.2. The 21 participating countries from the Asia-Oceania region.

Country	Country
Australia	Mongolia
Brunei Darussalam	New Caledonia
Cambodia	New Zealand
China (People's Republic of)	Papua New Guinea
Chinese Taipei	Philippines
Fiji	Russia
Indonesia	Singapore
Iraq	Sri Lanka
Japan	Thailand
Korea (Republic of)	Vietnam
Malaysia	

Table 6.3. The relative importance scores of criteria for a foot-and-mouth disease (FMD) control strategy according to the preferences of 21 chief veterinary officers (CVOs) or their representatives from the Asia-Oceania region.

Criteria and indicators	**Minimum**	**Median**	**Maximum**
Epidemiologic	50	90	100
Size of FMD outbreak area	45	90	100
Duration of FMD outbreak	10	80	100
Number of infected farms	30	78	98
Number of infected animals	20	60	98
Number of depopulated farms	5	40	80
Number of depopulated animals	5	30	95
Economic	40	85	100
Cost of control measures	30	80	100
Farm loss from movement restriction	5	75	100
Farm loss from depopulation	5	70	90
Industry loss from movement restriction	30	70	93
Export loss	5	50	100
Tourism loss	5	20	90
Social-environmental	25	80	98
Mental health of affected farmers	5	70	100
Mental health of the public	10	60	100
Welfare of infected animals	5	60	100
Welfare of non-infected animals	5	50	90
Air pollution	5	50	90
Ground pollution	0	50	100

Table 6.4. Standardized and weighted scores of foot-and-mouth disease (FMD) control strategies in the epidemiologic criterion.

Epidemiologic indicators	Weight	Baseline Strategy		0.5 kilometre slaughtering		1 kilometre slaughtering		5 kilometre slaughtering		30 day stop movement		60 day stop movement		Ring vaccination	
		S#	W#	S	W	S	W	S	W	S	W	S	W	S	W
Size of FMD outbreak area	90	0.07	1.01	0.06	0.85	0.00	0.00	0.11	1.63	0.06	0.85	0.06	0.89	0.02	0.31
Duration of FMD outbreak	80	0.39	5.20	0.00*	0.00*	0.00*	0.00*	0.34	4.53	0.00*	0.00*	0.39	5.20	0.40	5.33
Number of FMD-infected farms	78	0.70	9.08	0.00	0.00	0.22	2.87	0.80	10.36	0.44	5.75	0.70	9.04	0.70	9.07
Number of FMD-infected animals	60	0.63	6.31	0.00	0.00	0.10	0.97	0.74	7.35	0.50	5.01	0.62	6.18	0.64	6.44
Number of depopulated farms	40	0.36	2.40	0.65	4.31	0.55	3.66	0.03	0.23	0.00	0.00	0.36	2.38	0.37	2.46
Number of depopulated animals	30	0.17	0.87	0.81	4.04	0.73	3.66	0.00	0.00	0.03	0.14	0.17	0.86	0.18	0.88
Overall		2.32	24.87	1.52	9.20	1.60	11.16	2.02	24.10	1.03	11.75	2.30	24.55	2.31	24.49

S: Standardized score, W: weighted score.

*: scores defined as zero because those FMD-control strategies did not control the FMD outbreak within the simulation period.

Table 6.5. Standardized and weighted scores of foot-and-mouth disease (FMD) control strategies in the economic criterion.

Economic indicators	Weight	Baseline Strategy		0.5 kilometre slaughtering		1 kilometre slaughtering		5 kilometre slaughtering		30 day stop movement		60 day stop movement		Ring vaccination	
		S#	W#	S	W	S	W	S	W	S	W	S	W	S	W
Cost of control measures	80	0.55	7.28	0.36	4.75	0.39	5.13	0.40	5.36	0.00	0.00	0.13	1.76	0.56	7.43
Farm loss from movement restriction	75	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.70	8.75	0.40	5.00	0.00*	0.00*
Farm loss from depopulation	70	0.55	6.43	0.37	4.26	0.39	4.56	0.41	4.79	0.00	0.00	0.13	1.57	0.55	6.43
Industry loss from movement restriction	70	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.70	8.17	0.40	4.67	0.00*	0.00*
Export loss	50	0.39	3.25	0.00*	0.00*	0.00*	0.00*	0.34	2.83	0.00*	0.00*	0.39	3.25	0.40	3.33
Tourism loss	20	0.39	1.30	0.00*	0.00*	0.00*	0.00*	0.34	1.13	0.00*	0.00*	0.39	1.30	0.40	1.33
Overall		1.88	18.26	0.73	9.01	0.78	9.69	1.49	14.11	1.40	16.92	1.84	17.55	1.91	18.52

S: Standardized score, W: weighted score.

*: scores defined as zero because those FMD-control strategies applied the movement restriction for whole simulation period.

Table 6.6. Standardized and weighted scores of foot-and-mouth disease control strategies in the social-environmental criterion.

Social-environmental indicators	Weight	Baseline strategy		0.5 kilometre slaughtering		1 kilometre slaughtering		5 kilometre slaughtering		30 day stop movement		60 day stop movement		Ring vaccination	
		S#	W#	S	W	S	W	S	W	S	W	S	W	S	W
Mental health of affected farmers	70	0.36	4.20	0.65	7.54	0.55	6.40	0.03	0.41	0.00	0.00	0.36	4.16	0.37	4.31
Mental health of the public	60	0.70	6.98	0.00	0.00	0.22	2.21	0.80	7.97	0.44	4.42	0.70	6.96	0.70	6.97
Welfare of infected animals	60	0.70	6.98	0.00	0.00	0.22	2.21	0.80	7.97	0.44	4.42	0.70	6.96	0.70	6.97
Welfare of non-infected animals	50	0.36	3.00	0.65	5.38	0.55	4.57	0.03	0.29	0.00	0.00	0.36	2.97	0.37	3.08
Air pollution	50	0.17	1.45	0.81	6.73	0.73	6.10	0.00	0.00	0.03	0.24	0.17	1.43	0.18	1.47
Ground pollution	50	0.17	1.45	0.81	6.73	0.73	6.10	0.00	0.00	0.03	0.24	0.17	1.43	0.18	1.47
Overall		2.46	24.06	2.92	26.38	3.00	27.59	1.66	16.64	0.94	9.32	2.46	23.91	2.50	24.27

S: Standardized score, W: weighted score.

Table 6.7. Weighted overall scores and rankings of foot-and-mouth disease control strategies.

Criteria	Weight	Baseline Strategy		0.5 kilometre slaughtering		1 kilometre slaughtering		5 kilometre slaughtering		30 day stop movement		60 day stop movement		Ring vaccination	
		Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Epidemiologic	90	22.38	1	8.28	7	10.04	6	21.69	4	10.58	5	22.10	2	22.04	3
Economic	85	15.52	2	7.66	7	8.24	6	11.99	5	14.38	4	14.92	3	15.74	1
Social-environmental	80	19.25	4	21.10	2	22.07	1	13.31	6	7.46	7	19.13	5	19.42	3
Weighted overall		57.15	2	37.04	6	40.35	5	46.99	4	32.42	7	56.15	3	57.20	1

Table 6.8. Weighted overall scores and rankings of foot-and-mouth disease control strategies for the different simulation results.

Criteria	Baseline strategy		0.5 kilometre slaughtering		1 kilometre slaughtering		5 kilometre slaughtering		30 day stop movement		60 day stop movement		Ring vaccination	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
5th percentile of simulation results														
Epidemiologic	28.22	1	8.90	6	9.44	5	25.11	3	6.21	7	24.49	4	27.07	2
Economic	18.98	2	7.89	7	8.50	6	15.36	4	14.88	5	25.71	1	18.74	3
Social-environmental	30.13	1	22.83	4	21.73	5	19.69	6	2.56	7	28.91	3	30.08	2
Weighted overall	77.33	2	39.62	6	39.67	5	60.16	4	23.65	7	79.11	1	75.89	3
50th percentile of simulation results #														
Epidemiologic	22.38	1	8.28	7	10.04	6	21.69	4	10.58	5	22.10	2	22.04	3
Economic	15.52	2	7.66	7	8.24	6	11.99	5	14.38	4	14.92	3	15.74	1
Social-environmental	19.25	4	21.10	2	22.07	1	13.31	6	7.46	7	19.13	5	19.42	3
Weighted overall	57.15	2	37.04	6	40.35	5	46.99	4	32.42	7	56.15	3	57.20	1
95th percentile of simulation results														
Epidemiologic	15.45	1	8.56	5	8.73	4	15.45	1	3.05	7	5.87	6	14.71	3
Economic	9.98	3	7.43	7	7.79	6	8.02	5	14.38	1	10.86	2	9.89	4
Social-environmental	24.34	3	27.25	1	24.73	2	17.66	5	2.28	7	5.28	6	24.34	3
Weighted overall	44.90	1	37.79	3	36.30	5	37.60	4	19.25	7	20.95	6	44.07	2

Default input simulation results.

Chapter VII

7 General discussion

7.1 Overview

Decisions regarding transboundary livestock disease control strategies are different from personal decisions, such as buying groceries, in important ways: the stakes are high and the outcome of a decision will affect people in different fields. For example, culling infected animals to control foot-and-mouth disease (FMD) will affect not only the farmers whose animals are culled, but also the public and workers in abattoirs, transportation, and tourism. As a result, making decisions about disease control strategies can be challenging. The multi-criteria decision analysis (MCDA) process provides a way to take various criteria into account for making transparent, repeatable decisions. This makes MCDA particularly useful when decisions about disease control involve public resources, because those decisions require us to collaborate with stakeholders; in those situations MCDA can be used to stimulate discussion. Successful disease control strategies are based on agreement between stakeholders and on a supportive relationship between stakeholders and decision makers. If control strategies are not supported by stakeholders, they will be less effective than expected and may even fail completely. Decision makers need to address the stakeholders' various preferences for suitable control strategies. For decision makers worried about a defensible process, MCDA provides a way to organise what may seem like an overwhelming surge of input about many issues from many different people. For stakeholders worried about how they will be affected by the decision, MCDA offers a guideline about what they can expect from a decision making process.

Until recently, methods to evaluate disease control strategies have been focused on single measures of efficiency, such as strategies with the lowest cost or the lowest disease impact. In practice, decision makers need to consider the various impacts simultaneously. This thesis provides an example of an MCDA applied to a transboundary livestock disease, using the example of the control of FMD. The goal of the study has been to describe an approach to a complex decision problem as choices among FMD-control strategies, to provide tools that will support the reliable process, and ultimately to contribute more transparent decision making. FMD-control strategies were evaluated for each of three criteria: epidemiologic, economic, and socio-environmental. The results were expressed as comparable scores, which were merged to evaluate the overall effectiveness of each FMD-control strategy, and the FMD-control strategies were ranked according to overall effectiveness. The findings of the research showed how MCDA could be used to control FMD, including selecting stakeholders, constructing criteria, measuring criteria, and comparing the effectiveness of FMD-control strategies. These processes were reliable, transparent, and reproducible ways of making decisions about FMD-control strategies. In addition, the MCDA process described in this study could be repeated as views and opinions change. For example, public opinion around culling of animals may change, so the weighting applied to the number of animals destroyed may increase. Furthermore, once the framework has been established, MCDA may be used in the face of an outbreak as a real-time decision making method for choosing control strategies for transboundary livestock diseases.

7.2 The findings in the study

Because stakeholders play an important role in a MCDA, it is important to understand their preferences. **Chapter 3** presents a descriptive analysis of the preferences of chief veterinary officers (CVOs) in the Asia-Oceania region. CVOs were selected as stakeholders in the study because they are usually the final decision makers for nationally implemented disease control strategies. A questionnaire was designed to quantify preferences for criteria associated with FMD-control strategies. Criteria were categorised as epidemiologic, economic, and social-environmental. The CVOs in Asia-Oceania region identified the epidemiologic criterion as the most important of the three, with the size of the FMD-infected area, defined as the geographical size of FMD outbreak area, considered more important than other epidemiologic indicators. CVOs from countries where FMD was not endemic considered the economic criterion more important than those from countries that had experienced FMD.

When MCDA is applied to disease control strategies, it requires the measurement of criteria to compare the effectiveness of control strategies. **Chapter 4** describes the construction of an epidemiologic model of FMD spread to measure the epidemiologic effectiveness of FMD-control strategies. The baseline FMD-control strategy was designed as a three kilometre radius of pre-emptive slaughtering, 100 days of movement restriction, and blanket vaccination, based on the 2010/11 FMD epidemic in the Republic of Korea. Alternative FMD-control strategies also included pre-emptive slaughtering, movement restriction, and vaccination; however, the levels of each of these control options differed. The simulation results were expressed as the number of FMD-infected, depopulated, and vaccinated farms and animals, and the duration of the FMD epidemic.

According to the simulation results, the baseline FMD-control strategy accurately represented the 2010/11 FMD epidemic in two ways: 1) the median number of simulated FMD-detected farms was the same as the number of detected farms during the actual FMD epidemic, and 2) the simulated epidemic curve was similar to the actual epidemic curve of the 2010/11 FMD epidemic. Thus, the constructed model could be used as a reference for evaluating the effectiveness of alternative FMD-control strategies. Among the alternative FMD-control strategies considered was a pre-emptive slaughtering area comprising a five kilometre radius around an FMD-infected farm, with movement restriction of 100 days, and this resulted in the fewest FMD-infected farms. However, the resources required for this strategy, including equipment and labour, might be larger than the other strategies.

The increase in resources required by the alternative FMD-control strategy would also increase the overall cost of the control strategy. The cost-effectiveness of FMD-control strategies is evaluated in **Chapter 5.** If all FMD-control strategies can eradicate FMD in the study area, the most cost-efficient strategy then becomes the one with the least cost. CE analysis showed that ring vaccination in a band from three to five kilometres around FMD-infected farms was the most cost-efficient among the alternative FMD-control strategies. The other FMD-control strategies, in decreasing order of economic efficiency, were five kilometre slaughtering, 30 day stop movement, and 60 day stop movement strategy. The 0.5 kilometre and one kilometre slaughtering strategy were excluded in the analysis because these did not control FMD spread during the simulations.

Chapters 4 and **5** identify the most effective epidemiologic and economic control strategies. A strategy involving pre-emptive slaughtering within a five kilometre radius of FMD-infected farms was the most epidemiologically efficient, whereas the ring vaccination strategy was the most economically efficient. If decision makers consider the epidemiologic criterion more important than the economic criterion, a five kilometre slaughtering strategy will be better option than the ring vaccination. However, if decision makers consider the economic criterion more important than the epidemiologic criterion, a five kilometre slaughtering strategy will not be a good control option. Because decision making rarely rests entirely on just one factor, a structured decision making process was needed for decision makers to compare the differing effectiveness of FMD-control strategies in a scientific manner.

Chapter 6 describes the MCDA process for choosing the optimal FMD-control strategy by combining the results from **Chapters 3**, **4**, and **5**. FMD-control strategies were evaluated by epidemiological, economic, and social-environmental criteria using the perspectives of the CVOs. The results of **Chapter 3** were used to measure the weight of epidemiologic, economic, and social-environmental indicators in MCDA. The results from **Chapters 4** and **5** were used to measure the epidemiologic and economic effectiveness of FMD-control strategies. These measurements were merged with the weight to calculate the overall score of each FMD-control strategy. As a result, FMD-control strategies were ranked according to their overall scores.

From the perspective of CVOs in the Asia-Oceania region, the most preferred FMD-control strategy was the ring vaccination strategy, which consisted of pre-emptive slaughtering within a three kilometre radius around FMD-infected farms, 100 days of movement restriction, and vaccinating all

FMD-susceptible animals in a band from three to five kilometres around FMD-infected farms. The most epidemiologically efficient FMD-control strategy was the FMD-control strategy, which comprised pre-emptive slaughtering within a five kilometre radius around FMD-infected farms, movement restriction of 100 days, and vaccinating all FMD-susceptible animals in the study area; however, this was not the most preferred FMD-control strategy by CVOs in Asia-Oceania region.

7.3 The application of MCDA

All decisions benefit from clear thinking about their context. Establishing a decision context means providing concise and complete statements of what matters to stakeholders when making a decision. It also encourages stakeholders to focus on the decision making process when evaluating control strategies for transboundary livestock disease. Thus, the first stage of MCDA is to focus on what matters for stakeholders rather than what should be done. The choice of FMD-control strategies is a typical case for MCDA because the FMD-control strategy is related to several criteria such as epidemiology, economy, or the environment.

Aside from establishing the decision context, developing a list of objectives is also important in MCDA. The objectives lay the foundation for engaging stakeholders and for evaluating alternatives. In the study, the objective of the MCDA was to choose the most preferred FMD-control strategy from the perspectives of chief veterinary officers (CVOs) in the Asia-Oceania region. Among several FMD-control strategies, CVOs had to choose the best strategy by comparing the effectiveness of strategies because financial and labour resources during an outbreak are limited.

Performance measures are used to assess alternative control strategies, taking into account the objectives. If the performance of alternatives is hard to quantify, then we need to find ways of evaluating their impact on the final decision. In the study, the performances of FMD-control strategies were measured scientifically, using both an epidemiologic model and economic analysis. Epidemiologic models of FMD spread have been frequently used to evaluate the epidemiologic effectiveness of FMD-control strategies in Australia (Garner and Beckett, 2005), New Zealand (Sanson et al., 2011), the Republic of Korea (Yoon et al., 2006), the United Kingdom (Morris et al., 2001), and the United States (Bates et al., 2003b). Similarly, economic analysis of FMD-control strategies has been used to evaluate the economic effectiveness of FMD-control strategies in Denmark (Boklund et al., 2013), France (Mahul and Durand, 2000), South Sudan (Barasa et al., 2008), the United Kingdom (Thompson et al., 2002), and the United States (Bates et al., 2003a).

Uncertainty arises in many ways as part of the MCDA process. Uncertainty due to ambiguity might be addressed through the structured steps of the MCDA process, such as establishing the decision context or identifying the alternatives to be appraised (Gregory et al., 2012). However, uncertainty due to a lack of information about the performance of alternatives might not be easily addressed. A good MCDA process will provide details of results with probabilities and will look for ways to improve the quality of information under the uncertainty created by a lack of information. When there is no available information to measure the performance of alternatives, it is better to find alternatives that work effectively despite the uncertainty rather than trying to analyse the uncertainty (Herath and Prato, 2006).

In an MCDA framework, stakeholders can make trade-offs more readily when they are sure a range of alternatives has been explored. In the context of disease control the trade-offs are complex; therefore, an iterative measurement of alternative performance would help stakeholders compare alternatives, explore trade-offs, and understand the decision making process. In the study, the alternatives (i.e. FMD-control strategies) were from the 2010/11 FMD outbreak in the Republic of Korea. Thus, the CVOs from the Republic of Korea can make trade-offs regarding decisions about FMD-control strategies based on the results of the current study.

An MCDA process seeks to incorporate information and knowledge from a variety of resources. The core of an MCDA is to provide decision makers with insights into decision problems and feasible alternatives, including their effectiveness. If something is important, then a way should be found to estimate the consequences of alternatives for that concern in an MCDA. In many cases, MCDA leads to a clear and early preference for one alternative. The practical guidelines and examples in the study should help encourage interested readers to apply MCDA to decision making problems.

7.4 Critique of the study

7.4.1 Assumptions and limitations of MCDA

The MCDA process applied in this study was mostly deterministic and assumed that stakeholders have near perfect knowledge of the information involved in a given decision problem. However, even under such a favourable assumption, there might still be uncertainty in the results of the MCDA. Different methods of analytic procedures, such as standardizing the measurements or calculating the overall scores of alternatives, may result in different conclusions for the same problem. In other words, a single method may not always ensure the best decision. What can be done is to analyse the behaviour of the numerical methods under certain evaluative criteria that are motivated by accepted notions of logical stability (Triantaphyllou, 2000). By comparing results from different analytic procedures, scientists can evaluate and analyse the impact of those procedures.

Every MCDA has a subjective element because the final decision may depend on its key elements and the preferences of stakeholders (Gregory et al., 2012). Specifically, while stakeholders may give considered answers to their weightings, they are by their very nature personal opinions and therefore subjective. However, all decision making frameworks have a subjective element. To illustrate, a person who makes a decision based on an epidemiologic model has decided that the only criteria are epidemiologic. The difference between this and an MCDA is that in an MCDA framework decision the value-based elements of management decisions in ways that are systematic, consistent, and transparent. In addition, the tool would allow the preferences of different stakeholders such as farmers, economists, or the public to be used when addressing the subjectivity. The next step of the study is to collect the preferences of non-government stakeholders, such as industry representatives, farmers, and the general public, for FMD-control strategies and to evaluate FMD-control strategies from their perspectives.

A commitment to utilize MCDA for decision making, resolution of disease control, and other veterinary policy issues is lacking. Most applications of MCDA are funded by the government and advanced applications are limited to post-graduate research. Most policy makers may not appreciate and understand advanced decision making approaches. Even if policy makers are predisposed to using MCDA, its adoption is likely to be hindered because discussions about disease control strategy are still dominated by approaches such as benefit-cost analysis for assessing the economic efficiency of a control strategy. In other words, reliance on traditional methods may hinder uptake of new analytical approaches such as MCDA in veterinary sciences. However, enthusiasm for using MCDA in veterinary sciences appears to be increasing because of the nature of veterinary decision problems such as choosing a disease control strategy. The wider application of MCDA stems from its ease of use. Advancements in MCDA applications, such as using a computer-based MCDA tool with graphical user interface, would increase the understanding and use of MCDA for veterinary science.

7.4.2 Improving the epidemiologic model of FMD spread

The epidemiologic model in the study was constructed based on the 2010/11 FMD outbreak in the city of Andong, Republic of Korea. Model parameters such as the number of FMD-susceptible animals are likely to differ by province, so to increase the validity of the model, it should consider these differences. Fundamental information from each province, including the location of farms, available equipment and labour for applying control measures, movement patterns of animals, or the number of FMD-susceptible animals would need to be collected to parameterise the model for the whole country.

The epidemiologic model in the current study was a simulation model. The simulation software, InterSpread Plus, was designed to calculate the simulated number of disease infected farms mathematically. All farms in the model have a pre-determined probability of disease infection, which considers the distance from the infected farm and the infectivity of the disease agent. However, the model does not consider protection provided by enhanced biosecurity at the individual farm level. For instance, all farms close to an infected farm will have the same probability of infection, even if farms have varying levels of infection risk due to on-farm biosecurity practices. Statistical models could overcome this limitation of mathematical model by applying different disease infection probabilities to individual farms. The disease infection probability of each farm would be set based on its geographical closeness to an infected area, the frequency of movement, the infectivity of the disease agent, the history of the disease outbreak, and the biosecurity level of farms. A statistical model of disease spread would require intensive and detailed farm information but could provide more informative simulation results.

7.4.3 Indirect economic impacts of FMD-control strategies

In this study, the cost-effectiveness of FMD-control strategies was only evaluated based on the direct economic impacts of the FMD-control strategies. The direct economic impacts are the operational cost of disease control strategies, such as compensation cost for culling animals, labour and equipment costs for control measures, or management cost for carcass disposal. However, a disease outbreak will incur additional indirect economic impacts. These indirect impacts might include loans to individual farmers to re-populate their farms, decreases in domestic meat consumption, diminished future production, bans on exporting animal products, or a decrease in the number of tourists. The cost-effectiveness of individual FMD-control strategies may be different when indirect economic impacts are considered alongside direct impacts. However, it is not straightforward to estimate the indirect costs incurred during an outbreak. The quantification of social costs, such as a decrease in domestic meat consumption, is related to other industries. As a result, the information required to quantify the indirect economic impact is intensive and large. To increase the validity of the economic analysis presented in **Chapter 5**, a further survey of the financial status of farms and the social cost of disease outbreaks is recommended.

7.5 The future

For successful research on and application of MCDA, one needs a deep understanding of both the numerical measurement of alternatives and the cognitive aspects of the decision making process. The present study examined the numerical aspects and some of the cognitive issues involved in decision making about FMD-control strategies. More research and application of such methods to other decision making problems in veterinary science will follow. Wider use of MCDA would enhance the understanding of decision making processes for stakeholders and the possibility of achieving more efficient decision making for disease control strategies, and it would facilitate collaborative decision making among stakeholders. Adopting MCDA for veterinary decision making problems is affected by epidemiologic, economic, and social issues. The complexity of veterinary decision making problems will accelerate the use of MCDA. In addition, as demand increases for reliable and transparent decision making processes for veterinary decision making problems, there will be greater motivation to use MCDA. More work is needed to ensure that analytical procedures such as measuring criteria, standardizing measurements, or calculating the overall effectiveness of alternatives are applied effectively in MCDA. Specific issues that need to be addressed include ways to increase stakeholder participation and provision of graphical user interfaces that help understanding and use of MCDA. For example, Ozturk and Batuk (2011) developed a geographical information systems MCDA tool that used graphical user information systems to increase participation of stakeholders and to improve a real world model of flood vulnerability in the South Maramara Basin, Turkey. The authors noted that this type of tool could play a pivotal role in managing disasters. In veterinary science, a tool with a graphical user interface could also allow a range of stakeholders to provide inputs into decision making for control of transboundary livestock diseases and thereby improve the utility of MCDA.

7.6 Conclusion

This study has addressed various topics associated with selecting FMD-control strategies. In light of the findings, the following conclusions are provided:

1. **Chapter 3** showed that the 21 CVOs in the Pacific-Asia region who participated in the questionnaire evaluating preferences for FMD-control strategies preferred the epidemiological criterion over the economic and social-environment criteria. The CVOs considered epidemiologic indicators, in particular the size of FMD outbreak area, more important than economic or social-environmental indicators. The relative importance of the indicators measured in this chapter was used to evaluate FMD-control strategies in **Chapter 6**.

2. In **Chapter 4**, an epidemiologic model was constructed to evaluate the epidemiologic effectiveness of FMD-control strategies, and this reproduced the 2010/11 FMD outbreak in the city of Andong, Republic of Korea. The FMD-control strategy with a five kilometre radius of pre-emptive slaughtering, 100 days of movement restriction, and blanket vaccination predicted the fewest FMD-infected farms. In addition, increasing the number of farms depopulated per day reduced the simulated number of FMD-infected farms. The simulation results were used to evaluate FMD-control strategies in **Chapter 6**.

3. In **Chapter 5**, an economic analysis was applied to the results of the epidemiologic modelling to compare the cost-effectiveness of FMD-control strategies. The FMD-control strategy with a three kilometre radius of pre-emptive slaughtering, 60 days of movement restriction, and vaccination in a band from three to five kilometres around FMD-infected farms was more cost effective than the other FMD-control strategies. The cost of compensation paid to farms for slaughtered animals comprised the majority of the cost of each FMD-control strategy. The results of the economic analysis were used to evaluate FMD-control strategies in **Chapter 6**.

4. Using the results from the previous chapters, **Chapter 6** applied an MCDA for controlling FMD. FMD-control strategies were ranked using the preferences of 21 CVOs in the Asia-Oceania region (from **Chapter 3**) with epidemiologic, economic, and social-environmental criteria. The FMD-control strategy comprising a three kilometre radius of pre-emptive slaughtering, 100 days of movement restriction, and vaccination in a band from three to five kilometres around FMD-infected farms was the most preferred control strategy. This implies that MCDA could provide a decision support tool for control of transboundary livestock disease such as FMD.

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