Multi-criteria decision analysis to evaluate foot and mouth disease control strategies with the perspectives of chief veterinary officers in the Asia–Oceania region

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Summary

The objective of this study was to evaluate the effectiveness of foot and mouth disease (FMD) control strategies using multi-criteria decision analysis (MCDA). The FMD control strategies were evaluated for epidemiological, economic and social–environmental criteria, accounting for the preferences of chief veterinary officers (CVOs) from the Asia–Oceania region, with the preferences quantified using a questionnaire study. Previously reported simulation results of an FMD epidemic were used to measure the epidemiological effectiveness of FMD control strategies. The simulated FMD epidemic results, such as the number of infected farms, the duration of the epidemic and the outbreak area, for a number of FMD control strategies were compared. Based on previous simulation and economic modelling results and incorporating a literature search to quantify the social and environmental outcomes of an FMD outbreak, MCDA analysis was conducted to evaluate control strategies. According to the overall score in the MCDA results, an FMD control strategy which consisted of a 3-km radius of pre-emptive slaughter, 100 days of movement restriction and vaccinating all FMD-susceptible animals (baseline strategy) was the preferred strategy, with the highest overall score of 62.99. In contrast, the same duration of movement restriction and vaccination strategy with a 0.5-km radius of pre-emptive slaughter was least preferred, with the lowest overall score of 37.05. The evaluation of the FMD control strategies presented here using MCDA has provided scientific evidence for selecting an appropriate baseline FMD control strategy, based on the preferences of CVOs.

Keywords

Chief veterinary officer (CVO) – Decision analysis – Foot and mouth disease (FMD) control – Multi-criteria decision analysis (MCDA).

Introduction

Foot and mouth disease (FMD) remains one of the most important diseases in the livestock industry. In an outbreak, FMD can spread rapidly between susceptible animals; therefore, an instant implementation of control strategies is of critical importance. One way to ensure that control strategies are implemented quickly is to gain the support of stakeholders, through communication with decision makers (1). The failure to rapidly implement control strategies due to communication failure was highlighted during the 2001 FMD epidemic in the Netherlands, where considerable time was spent by the government convincing farmers to adopt a pre-emptive slaughter strategy (2). Consequently, the control of FMD in this outbreak was delayed.

Decisions regarding control strategies need to be in place prior to an outbreak. Decision analysis is used to organise the different views of stakeholders in a rational and scientific manner and enable the effective communication of these decisions. One helpful tool in this respect is multi-criteria decision analysis (MCDA), which provides a systematic methodology to combine information about a problem with solutions and with stakeholders' views in order to solve decision-making problems. The use of MCDA has been reported in multiple fields, including ecology (3) and environmental science (4). However, MCDA is an emerging methodology in veterinary science. In recent years MCDA has been applied to animal health problems, particularly infectious diseases, for supporting decisions regarding disease control strategies or prioritising infectious diseases for control by including the preferences of stakeholders. Mourits *et al.* (5) applied MCDA to evaluate control strategies for classical swine fever (CSF), focusing on the views of chief veterinary officers (CVOs) from France, Great Britain, Germany, Italy, Poland and Hungary. Cox *et al.* (6) applied MCDA to prioritise infectious diseases, based on control strategies and the likelihood of emergence associated with climate change, incorporating the preferences of academic experts and government officers in Canada. In their study, the social impacts of the diseases were quantified, and the diseases were ranked by the amount of impact.

Any delay in the implementation of control strategies due to disagreement between stakeholders can result in huge economic losses (7). Therefore, in order to be successful, FMD control strategies must rely on solid scientific evidence regarding control strategies and upon agreement between stakeholders and decision makers. The objective of this study was to describe an MCDA process for supporting decisions regarding FMD control strategies. The stakeholders investigated in this study were CVOs from the Asia–Oceania region.

Materials and methods

Overview (background and general framework)

Decisions regarding control strategies for infectious animal diseases, such as FMD, are suitable for assessment using MCDA. Decision makers 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, slaughter of FMD-infected animals or pre-emptive slaughter of FMD-susceptible animals, varies depending on how and when strategies are applied and on many other situation-specific variables. Additionally, the way in which effectiveness is evaluated is important. Using simulation modelling, Bates *et al.* (8) demonstrated that the pre-emptive slaughter of susceptible animals in order to control FMD spread may be more effective than vaccination or movement restriction. If pre-emptive slaughter were applied, the duration of the epidemic was shorter, and the number of infected farms was lower than if vaccination or movement restriction were used as control strategies. From an economic perspective, however, pre-emptive slaughter is more costly than either vaccination or movement restriction (9). Therefore, if a decision maker considered epidemiological issues to be more important than economic issues, pre-emptive slaughter would be a preferable control strategy. However, if a decision maker considered the economic implications to be more important, pre-emptive slaughter is not the best option. Consequently, decision makers need a method to compare the effectiveness of FMD control strategies in a scientific manner.

Multi-criteria decision analysis assists with decision making by systematically analysing a problem under consideration. The problem is broken into manageable pieces (criteria), and alternative options for solving the problem are evaluated for each criterion. In MCDA for disease control strategies, the evaluation is intended to measure the epidemiological or economic effectiveness of control strategies. The effectiveness of each disease control strategy across criteria is expressed as a numerical value, and these can be synthesised to estimate the overall effectiveness. The control strategies are then ranked according to their overall effectiveness. The MCDA methodology used in the current study follows the eight steps described by Mourits *et al.* (5): *1)* determining the decision-making context, *2)* identifying alternatives to be appraised, *3)* determining the criteria, *4)* measuring the criteria, *5)* standardising the measurements, *6)* weighting the criteria, *7)* calculating the overall scores and ranking and *8)* performing a sensitivity analysis.

Determining the decision-making context (step 1)

The study focused on performing MCDA to evaluate the effectiveness of FMD control strategies. In previous studies, FMD control strategies have been evaluated with epidemiological criteria (8, 10, 11), economic criteria (9, 12, 13) and social criteria (14), respectively.

However, 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 FMD endemic. The current study incorporated the approaches taken by previous studies (10) and quantified the overall effectiveness of FMD control strategies in conjunction with the preferences of stakeholders. The stakeholders in the study were CVOs from the Asia–Oceania region, because they are the final decision makers for selecting an FMD control strategy.

Identifying alternatives to be appraised (step 2)

The baseline FMD control strategy was designed based on the FMD control strategy implemented during the 2010–2011 FMD epidemic in the Republic of Korea. For the baseline strategy, the study area was Andong-si; the size of the area was about 1,520 km^2. The baseline strategy comprised a 3-km radius of pre-emptive slaughter around an infected farm, 100 days of movement restriction, involving a local movement standstill in the study area for 100 days from the day when the first FMD-infected case was confirmed, and vaccinating all FMD-susceptible animals in the study area. Subsequently, each control measure included in the baseline strategy was altered to create alternative FMD control strategies. Alterations in control measures were as follows: *1)* pre-emptive slaughter within a radius of 0.5 km, 1 km and 5 km of an infected farm; *2)* movement restriction durations of 30 days and 60 days and *3)* ring vaccination within a 5 km radius of an infected farm (Table I).

Table I

Details of baseline and alternative control strategies for foot and mouth disease

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

*: vaccinating all FMD-susceptible animals in Andong-si, Republic of Korea
+: movement restriction (movement of FMD-susceptible animals in the study area [Andong-si, Republic of Korea] was restricted for a certain period)
#: vaccination of all FMD-susceptible animals within a 5-km radius of FMD-infected farms
FMD: foot and mouth disease

Determining the criteria (step 3)

The impact of FMD control strategies is related to epidemiological, economic and social–environmental issues (5), so these three groups of criteria were applied in the current study. First, the epidemiological criteria required that the FMD control strategy was efficient for reducing the duration of an FMD epidemic, the size of the FMD-infected area, the number of FMD-infected farms and animals, and the number of depopulated farms and animals. Second, the economic criteria identified the impact of any FMD control strategy on the economic performance of the farm, industry and country. The operating cost of FMD control strategies, farm losses from the amount of depopulated animals, farm losses from movement restrictions, industry losses from movement restrictions, losses from export bans and losses from decreased tourism were included in the economic criteria. Lastly, the social–environmental criteria indicated the impact of FMD control strategies on social–environmental issues. The mental health of FMD affected farmers and the public, the welfare of FMD-infected and non-infected animals, and air and ground pollution from carcass disposal were included in the social–environmental criteria.

Measuring the criteria (step 4)

A simulation model was constructed to measure the epidemiological criteria for each FMD control strategy. State-transition simulation software, InterSpread Plus (EpiCentre, Massey University, Palmerston North, New Zealand), was used to simulate the FMD epidemic for each strategy. The simulation software has previously been used to simulate the spread of FMD between farms in the Republic of Korea (10, 11) and in the United Kingdom (13, 15). Simulation outcomes were expressed as the number of animals and farms that were infected, detected, slaughtered or vaccinated during the simulated FMD epidemic, and the duration of the disease epidemic. The median number of simulation outcomes was used to measure the effectiveness of FMD control strategies according to the epidemiological criteria. In brief, in the FMD epidemiological model, the infectivity of the FMD virus, contact between FMD-infected farms and FMD-susceptible farms, measures to control FMD and resource constraints such as a limit to the number of farms that can be vaccinated or depopulated per day were parameterised. Further information regarding the epidemiological modelling and the development of the epidemiological criteria can be found in the previous study (10).

A deterministic economic spreadsheet model was developed from the outcomes of the simulation model to measure the economic criteria. These results have been published elsewhere (12) but, briefly, the total farm losses due to the slaughter of infected animals were estimated using the total number of slaughtered animals as determined by the epidemiological model multiplied by the compensation cost per animal. Similarly, the economic losses from an export ban were estimated using the duration of the FMD epidemic as determined by the epidemiological model multiplied by the amount of economic losses per day. The costs associated with FMD control measures and economic losses due to the FMD epidemic were obtained from the Ministry of the Interior and Safety.

The social–environmental criteria were measured based on the literature review combined with the FMD epidemic results from the epidemiological model. The mental health of FMD affected farmers and the public, the welfare of FMD-infected and non-infected animals, and air and ground pollution from carcass disposal were included in the social–environmental criteria. The mental health of farmers was quantified by relating the mental health of FMD-affected farmers to the number of FMD-infected farms. Van Haaften *et al.* (16) used a survey to determine the mental health status of 661 dairy farmers after the 2001 FMD epidemic in the Netherlands. According to their study, farmers experienced 'post-traumatic stress at levels requiring professional help'. Similarly, Mort *et al.* (17) surveyed the mental health of 54 people in North Cumbria, an outbreak area during the 2001 FMD epidemic in the United Kingdom. In their study, people experienced mental health problems, such as depression or stress. In the current study, the mental health of FMD-affected farmers and the public was expected to worsen as the simulated number of depopulated farms increase in the epidemiological model. Crispin *et al.* (18) described the animal welfare issues related to the FMD control strategy used during the 2001 FMD epidemic in the United Kingdom. The study identified that improper or inappropriate slaughter methods were applied during the epidemic because the number of animals that were designated to be culled was so large. Therefore, slaughter should be applied as early as possible to minimise FMD spread. In the current study, if the simulated number of depopulated animals increases then animal welfare will worsen. The environmental criteria were estimated from an experimental study which quantified the amount of contaminants due to carcass disposal. Yuan *et al.* (19) examined the concentrated contaminants in the discharges from buried carcasses. In their study, residues such as veterinary antimicrobials, including monensin, could be potential contaminants of the soil near the burial area.

Standardising the measurements (step 5)

Standardisation, the transformation of raw measurements into one common measurement unit, was applied so that measurements used in the different scales were comparable. The measurement scales of each criterion were different. For example, epidemiological units, such as the number of FMD-infected farms or the duration of the FMD epidemic, were used to measure the effectiveness of FMD control strategies according to the epidemiological criteria. However, the amount of economic loss due to the FMD epidemic was measured as monetary units in the economic criteria. Thus, standardisation was applied in which the measurement of each criterion was divided by the highest measurement of the criterion in each group (i.e. epidemiological, economic and social–environmental). As a result, the scores were transformed to obtain a range from zero to one. The standardised score was then deducted from one to in order to ensure that the FMD control strategy with the highest score indicated the preferred strategy.

Weighting the criteria (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 was quantified and used to weight the criteria. The questionnaire quantified the relative importance of epidemiological, economic and social–environmental criteria associated with FMD control strategies. The scale of scores was defined from 0 to 100, and a higher score indicated greater importance. This study has been reported previously (20) 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 representatives of CVOs from the Asia–Oceania region completed the survey anonymously (Table II). The responses to the questionnaire were collected on 19 November 2013 and the response rate was 100%. The median scores for the relative importance of the criteria were used as weights.

Table II

The 21 participating countries from the Asia–Oceania region

Country	
Australia	Mongolia
Brunei	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	

Calculating the overall scores and ranking (step 7)

The weighted scores of the FMD control strategies for the three groups of criteria were calculated as the standardised score multiplied by the weight of each criterion. The score of the FMD control strategies for each group (epidemiological, economic or social–environmental) was calculated by dividing the sum of the weighted scores by the number of criteria in the group (Equation 1). For example, if the number of epidemiological criteria was six, the score of an FMD control strategy for the epidemiological group was calculated as the sum of the six weighted scores and the summed score was divided by six. The FMD control strategies were ranked using the sum of the scores for the three groups: epidemiological, economic and social–environmental. When criteria are mutually independent and the scores for the criteria are measured in the same units, a sum of weighted scores is a commonly used method to calculate the overall scores of alternatives (21). A sum of weighted scores was appropriate for the current study because each score for a criterion was transformed onto the same scale using the standardisation.

$$V = \sum_{i=1}^{n}(w_i c_i / n) \qquad \text{(Eq. 1)}$$

V: overall score of alternatives, w_i: the weight for the ith criterion, c_i: the standardised score of the alternative for the ith criterion and n: the number of criteria

In addition to ranking of the FMD control strategies, the overall score for each FMD control strategy was compared in pairs and the dominance score was calculated as the difference between the overall scores of the FMD control strategies. A positive dominance of one FMD control strategy over another strategy indicated that the dominant strategy is preferred when compared with the other. A dominance score of zero implies no difference in preference between two FMD control strategies (5).

Performing a sensitivity analysis (step 8)

The overall scores of the FMD control strategies were based on the median value of the 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 scores of the FMD control strategies. The 5th and 95th percentile values of simulation outcomes, reflecting risk taking and risk averse individuals, were applied and these were used to calculate the scores of FMD control strategies. For example, all 5th percentile values of simulation outcomes were used to calculate the scores of FMD control strategies for epidemiological, economic and social–environmental criteria for risk taking individuals. The rankings of FMD control strategies for risk averse individuals were calculated in the same manner with the 95th percentile values of simulation outcomes. The rankings of FMD control strategies for the epidemiological, economic and social–environmental criteria with 5th and 95th percentile values were compared with the median value of the simulation results.

Results

Weights of the criteria

The weighted scores for the epidemiological, economic and social–environmental criteria are shown in Table III. The highest median weights for the criteria were for the size of the FMD outbreak area (90, range from 45 to 100) in the epidemiological group, the cost of FMD control measures (80, range from 30 to 100) in the economic group, and the mental health of affected farmers (70, range from 5 to 100) in the social–environmental group. However, there was variability in the weights attributed by the CVOs, with a large range of scores.

Table III

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

Criteria	Minimum	Median	Maximum
Epidemiological			
Size of FMD outbreak area	45	90	100
Duration of FMD	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			
Cost of control measures	30	80	100
Farm losses from movement restriction	5	75	100
Farm losses from depopulation	5	70	90
Industry losses from movement restriction	30	70	93
Export losses	5	50	100
Tourism losses	5	20	90
Social–environmental			
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

Scores for foot and mouth disease control strategies

Among the epidemiological criteria, the strategy with a 5-km slaughter area had the highest score for the outcome of the area of the FMD epidemic. Ring vaccination was the highest scoring strategy for the outcome of duration of the FMD epidemic, and the 0.5-km slaughter area was scored highest for the outcome of the number of depopulated farms and the number of depopulated animals (Table IV). Among the economic criteria, ring vaccination was the highest scoring control strategy for the outcomes of cost of control measures, farm losses from depopulation, export loss and tourism decrease, and 30-day stopping of movement for farm and industry losses from movement restriction (Table V). The FMD control strategy with the highest score among the social–environmental criteria was the 0.5-km slaughter strategy for the outcomes of mental health of affected farmers, welfare of non-infected animals, air pollution and ground pollution, whereas the baseline strategy had the highest score for the welfare of infected animals (Table VI).

Table IV

Standardised and weighted scores of foot and mouth disease (FMD) control strategies: epidemiological criteria

Criteria	Weight	Baseline strategy		0.5-km slaughter		1-km slaughter		5-km slaughter		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 epidemic	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 slaughtered 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

S: standardised score
W: weighted score
*: the scores were effectively zero because these FMD control strategies did not control the FMD epidemic within the simulation period

Table V

Standardised and weighted scores of foot and mouth disease (FMD) control strategies: economic criteria

Criteria	Weight	Baseline strategy		0.5-km slaughter		1-km slaughter		5-km slaughter		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 losses 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 losses 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 losses 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 losses	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 losses	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

S: standardised score
W: weighted score
*: the scores were effectively zero because these FMD control strategies applied the movement restriction for the whole simulation period

Table VI

Standardised and weighted scores of foot and mouth disease control strategies: social–environmental criteria

Criteria	Weight	Baseline strategy		0.5-km slaughter		1-km slaughter		5-km slaughter		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

S: standardised score
W: weighted score

Overall scores and rankings of foot and mouth disease control strategies

The highest overall score for an FMD control strategy under the epidemiological criteria was for the baseline strategy, with an overall score of 24.87. For the economic criteria, the highest overall score for a control strategy was for ring vaccination, with a score of 18.52, and for the social–environmental criteria the control strategy with 1-km slaughter area had the highest overall score, at 21.19. Overall, the ranks of the FMD control strategies, in decreasing order, were the baseline strategy, ring vaccination, 60-day stop movement, 5-km slaughter, 1-km slaughter, 30-day stop movement, and 0.5-km slaughter (Table VII).

Table VII

Overall scores and rankings of foot and mouth disease control strategies

Criteria	Baseline strategy		0.5-km slaughter		1-km slaughter		5-km slaughter		30-day stop movement		60-day stop movement		Ring vaccination	
	Score	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**
Epidemiological	24.87	1	9.20	7	11.16	6	24.10	4	11.75	5	24.55	2	24.49	3
Economic	18.26	2	9.01	7	9.69	6	14.11	5	16.92	4	17.55	3	18.52	1
Social–environmental	19.86	3	18.84	5	21.19	1	16.23	6	9.32	7	19.75	4	19.96	2
Overall	62.99	1	37.05	7	42.04	5	54.44	4	37.99	6	61.85	3	62.97	2

The highest dominance score was 25.94, between the baseline strategy and the 0.5-km slaughter strategy, whereas the lowest dominance score was 0.02, between the baseline strategy and ring vaccination. The dominance scores of the baseline strategy in comparison with other FMD control strategies were all positive and the dominance scores of 0.5-km slaughter were all negative (Table VIII).

Table VIII

Dominance scores of foot and mouth disease control strategies

Strategies	Baseline strategy	0.5-km slaughter	1-km slaughter	5-km slaughter	30-day stop movement	60-day stop movement	Ring vaccination
Baseline strategy	–	25.94	20.95	8.55	25.00	1.14	0.02
0.5-km slaughter	–	–	–4.99	–17.39	–0.94	–24.80	–25.92
1-km slaughter	–	–	–	–12.40	4.05	–19.81	–20.93
5-km slaughter	–	–	–	–	16.45	–7.41	–8.53
30-day stop movement	–	–	–	–	–	–23.86	–24.98
60-day stop movement	–	–	–	–	–	–	–1.12

Sensitivity analyses

When the 5th percentile of the simulation results was used, the most preferred FMD control strategies were the baseline strategy for the epidemiological and social–environmental criteria and the 60-day stop movement strategy for the economic criteria. When the 95th percentile of simulation results was applied, the most preferred FMD control strategies were the baseline strategy for the epidemiological criteria, the 30-day stop movement strategy for the economic criteria and the 0.5-km slaughter strategy for the social–environmental criteria (Table IX).

Table IX

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

Criteria	Baseline strategy		0.5-km slaughter		1-km slaughter		5-km slaughter		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														
Epidemiological	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														
Epidemiological	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														
Epidemiological	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

Discussion

Multi-criteria decision analysis was applied to evaluate the effectiveness of FMD control strategies based on the preferences of key stakeholders: CVOs from the Asia–Oceania region. The FMD control strategies were designed on the basis of the actual FMD control strategy that was applied during the 2010–2011 FMD epidemic in the Republic of Korea. Three groups of criteria were used to assess alternative control strategies, epidemiological, economic and social–environmental, and the criteria were chosen based on previous studies (5). According to these criteria, the baseline strategy, which applied pre-emptive slaughter within a 3-km radius of an FMD-infected farm, 100 days of movement restriction and vaccination of all FMD-susceptible animals, was the preferred FMD control strategy. The effectiveness of FMD control strategies was measured based on a previous study involving simulation of FMD spread in the Republic of Korea (10), and this was used as a situation-specific example of FMD control strategy decision making. If a CVO considers only the epidemiological effectiveness of an FMD control strategy, pre-emptive slaughter within a 5-km radius of an FMD-infected farm, 100 days of movement restriction and vaccinating all FMD-susceptible animals might be the best choice. However, the national budget for applying an intensive FMD control strategy is limited and a massive slaughter of animals would not be acceptable to the public. Therefore, CVOs should choose an FMD control strategy with a consideration of epidemiological, economic and social–environmental factors at the same time. The evaluation of FMD control strategies using MCDA can provide scientific evidence for selecting an appropriate FMD control strategy.

The ring vaccination strategy can be used as an alternative to the baseline strategy because the difference in the dominance score between the baseline strategy and the ring vaccination strategy was only 0.02. The ring vaccination strategy requires fewer resources than the baseline strategy because only FMD-susceptible animals within a 5-km radius of an FMD-infected farm are to be vaccinated. The saved resources, such as labour or equipment, could be allocated to other

FMD control measures such as movement restriction or depopulation. The disadvantage of ring vaccination is that the FMD outbreak area might be larger than that of the baseline strategy. The weighted score for the size of outbreak area was 1.01 for the baseline strategy and 0.31 for ring vaccination. For decision makers who consider the size of the outbreak area to be more important than other criteria, ring vaccination might be the recommendable alternative.

A systematic process of MCDA, including identifying alternative disease control strategies, measuring the effectiveness of strategies, standardising the measurements, reflecting stakeholders' preferences and calculating the overall effectiveness of strategies, can be helpful for evaluating infectious animal disease control strategies. This process can be applied to other infectious diseases, beyond FMD. Mourits *et al.* (5) applied MCDA to evaluate CSF control strategies, incorporating the preferences of CVOs in Europe. Both the current study and the European study 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 this study may not be directly applied to other countries because the FMD control strategies were designed based on the reaction plan of the Republic of Korea, and the FMD dynamics may be different in other countries. However, the current study demonstrated how to rank FMD control strategies with the consideration of CVOs' preferences and simulation results. The CVOs' preferences for FMD control strategies may be similar in different regions. The CVOs from the Asia–Oceania region considered the epidemiological criteria, in particular the size of the FMD outbreak area and the duration of the FMD epidemic, to be the most important among the epidemiological, economic and social–environmental criteria. Similarly, the CVOs from Europe considered the epidemiological criteria, in particular the duration and the size of a CSF outbreak, to be the most important (5). The Korean CVO also considered the epidemiological criteria, in particular the number of infected farms, to be more important than economic or social–environmental criteria. The weights of epidemiological criteria such as the size of the FMD outbreak area or duration of the outbreak were higher than those of economic or social–environmental criteria, and the overall score of an FMD control strategy which could reduce the size of the FMD outbreak area or the duration of FMD was high.

The constraints on human or material resources for control of FMD are an important factor, so the current study considered these factors as economic criteria, such as the cost of FMD control measures and farm losses from depopulation or movement restriction. Generally, however, the CVOs were interested in the epidemiological effectiveness of control strategies, and consequently the control strategy with the highest epidemiological efficacy might be preferred over other control strategies. However, CVOs in Europe, in comparison to CVOs in the Asia–Oceania region, might consider disease morbidity to be more important because the countries in Europe are located close to each other. In addition, the disease status of countries might influence the preference of control strategies. The CVOs in disease-free countries may prefer preventive control strategies whereas the CVOs in disease-endemic countries may prefer a control strategy which can minimise the effects of a disease outbreak.

The MCDA methodology can be extended to examine the preferences of other stakeholders, including farmers, environmentalists or the public, as it may be expected that the preferences for disease control strategies may differ for different stakeholders. Farmers may prefer different epidemiological criteria to CVOs. Australian pig farmers were more focused on disease duration than the case fatality rate of disease (22). Therefore, farmers may prefer a control strategy that can shorten an epidemic, rather than reduce the mortality rate. Other stakeholders such as the public or environmentalists also have different preferences for livestock disease control strategies. During the FMD epidemic in 2001 in the Netherlands, the public opposed the application of pre-emptive slaughter because of concerns about animal welfare (2). Consequently, the public may prefer strategies that do not rely on slaughter. Therefore, the next step of the MCDA methodology used here is to measure the preferences of various stakeholders and those of stakeholders in different regions.

One limitation of the current study was the use of a linear aggregation of scores. Using a linear aggregation of scores to calculate the overall scores of alternatives requires an assumption that the criteria are mutually independent. While this measure has been used in previous studies (5, 23), this assumption of independence was violated for some criteria in the study. Nevertheless, a linear aggregation of scores was applied because it was the best way to calculate the overall effectiveness of FMD control strategies. The MCDA results were interpreted with consideration of the dependency between criteria. The dependency between criteria indicated that if one FMD control strategy was ranked high in the epidemiological group, that FMD control strategy might be also ranked high in the social–environmental group. The active participation of stakeholders in the selection of criteria or assigning values for criteria is required to quantify the degree of dependency, and this process was logistically unfeasible 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.

Conclusion

This study applied MCDA to evaluate the effectiveness of FMD control strategies, incorporating the preferences of CVOs from the Asia–Oceania region. The CVOs considered the epidemiological criteria, in particular the size of the FMD outbreak area, to be more important than economic or social–environmental criteria. The FMD control strategy that consisted of a 3-km radius of pre-emptive slaughter, 100 days of movement restriction and vaccinating all FMD-susceptible animals had the highest overall score, whereas the strategy with a 0.5-km radius of pre-emptive slaughter but the same movement restriction and vaccination area scored the lowest. When the 5th percentile of the simulation results was used instead of the median value (default simulation results) to evaluate FMD control strategies, the FMD control strategy that consisted of a 3-km radius of pre-emptive slaughter, 60 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 other infectious animal disease control strategies beyond FMD.

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