A decision tree to optimise control measures during the early stage of a foot-and-mouth disease epidemic

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Abstract

A decision tree was developed as a tool to support decision making on control measures during the first days after the declaration of an outbreak of foot-and-mouth disease (FMD). The objective of the tree was to minimise direct costs and export losses of FMD epidemics under several scenarios. These scenarios were based on important determinants in the development of epidemics and therefore defined by livestock and herd density in the outbreak region, the possibility of airborne spread, and the time between first infection and first detection.
The starting point of the tree was an epidemiological model based on a deterministic SIR approach. The effect of four control strategies on FMD dynamics was modelled. In addition to the standard control strategy of stamping-out and culling of high-risk contact herds, strategies involving ring culling within 1 km of an infected herd, ring vaccination within 1 km of an infected herd, and ring vaccination within 3 km of an infected herd were assessed. An economic model converted outbreak and control effects of farming and processing operations into estimates of direct costs and consequential export losses.
Results showed that animal density within the outbreak region is a very important determinant in deciding on the economically optimal control strategy. Ring vaccination is the economically optimal control strategy for **densely** populated livestock areas whereas ring culling is the economically optimal control strategy for **sparsely** populated livestock areas.

1. Introduction

Foot-and-mouth disease (FMD) is a highly contagious disease that infects many cloven-footed mammals, including cattle, pigs, sheep, goats, and deer. The virus has the potential to spread rapidly in susceptible populations. From previous economic works it is clear that FMD outbreaks generate considerable losses due to costs of disease control, productivity losses and constraints on international meat and livestock trade (Power et al., 1973; Krystynak et al., 1987; Berentsen et al., 1990; Garner et al., 1995; Mahul et al., 1999 & 2000). Recent examples of the devastating consequences of FMD are the epidemics in Great Britain and The Netherlands in 2001. In Great Britain nearly four million animals have been slaughtered and the disease spread over to 2030 livestock farms (Department for Environment, Food and Rural Affairs, 2001). During the Dutch epidemic about 265.000 animals had to be slaughtered and 26 farms were actually infected (Ministry of Agriculture, Nature Management and Fisheries, 2001). Another example is the epidemic which occurred in 1997 in Taiwan, in which more than four million pigs had to be slaughtered (Yang et al., 1999).
FMD is a difficult disease to control and eradicate because of the various mechanisms by which the virus can be transmitted (Sellers, 1971). The most common mechanism is the movement of infected animals to susceptible animals (Donaldson et al. 2001). Other spread mechanisms include the movement of contaminated animal products such as meat, offal and milk. FMD virus can also be transmitted mechanically, for example, by contaminated milking machines, by vehicles, especially those used for transporting animals, and by people. Another mechanism is airborne spread. Under certain epidemiological and climatic conditions FMD virus can be spread by the wind. Of all mechanisms spread by air is least controllable (Donaldson et al., 2001; Ferguson et al., 2001a; Sørensen et al., 2000 & 2001).

The objective of this study was to develop a tool to support decision making on control strategies during the early stage of an FMD epidemic. Early stage meant the first few days after the declaration of an outbreak. Successful eradication of an epidemic depends on the selected control strategy and on the time interval between diagnosis and implementation of the control strategy. Selecting an inadequate strategy may cause large additional economic losses (Mahul et al., 1999). Delayed implementation of control measures may cause extensive spread of the disease (Garner et al., 1995; Howard et al., 2000; Ferguson et al., 2001b). This means that it is very important for animal health authorities to make the right decision immediately after the first diagnosis. Usually there is no time to gather additional data to support decision making. Therefore, it is very essential to have an overall analytic structure for these kinds of situations beforehand. This paper presents such an analytic structure comprising a decision tree modelling approach using all information presumably available in the first three days after the declaration of an outbreak. By means of this approach the efficacy of disease control measures was evaluated in all kinds of scenarios. The efficacy was determined by modelling the epidemiological consequences and calculating the resulting direct costs and export losses. Scenarios were defined by important determinants in the development of epidemics that were found in literature.

The objective of the decision tree was to calculate the economically optimal control strategy for each scenario. Economically optimal meant that direct costs and export losses were minimised. The results of the decision tree can be used as yardsticks for deciding on control measures during possible FMD epidemics in the future.

2. Materials and methods

The modelling approach consists of three modules (see figure 1): an epidemiological module to simulate the disease dynamics, an economic module to convert outbreak and control effects into estimates of direct costs and export losses, and finally a decision tree module to optimise decisions on control strategies. These parts are described in sections 2.5 to 2.7. First the choice of virus strain, control strategies, regions and scenarios are founded in sections 2.1 to 2.4.

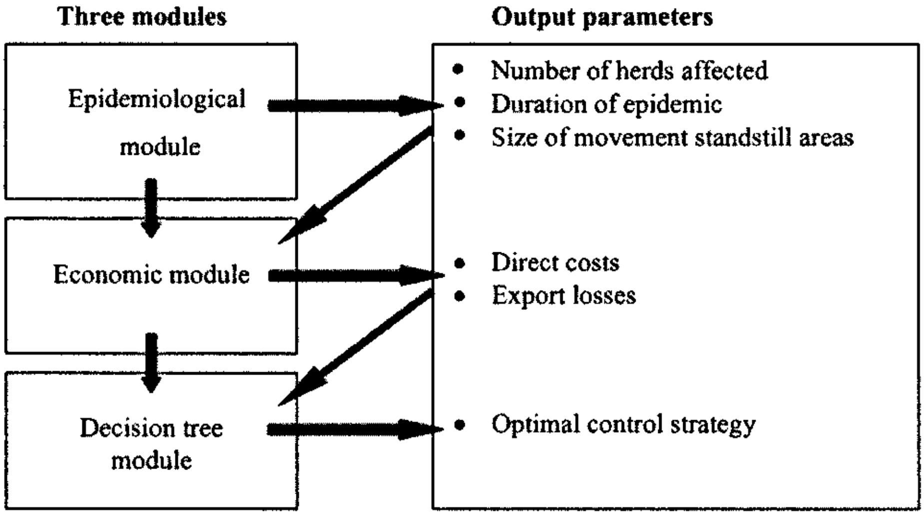

Figure 1. An overview of the modelling approach

2.1 Choice of virus strain

There are seven immunologically and serologically distinct types of FMDV: A, O, C, SAT1, SAT2, SAT3 and Asia 1. Within each serotype there are several subtypes. The disease caused

by different serotypes is clinically indistinguishable, although they vary somewhat in their epidemiological patterns (Sanson, 1993). Some strains of FMDV show a degree of natural adaptation to an animal species, with the result that the other species of animals appear to be more difficult to infect. An example of a pig-adapted virus strain was the strain that caused the Taipei China epidemic in 1997. No outbreaks were detected in cloven-hoofed animals other than pigs (Chen et al., 1999).
This study also confined attention to FMDV outbreaks in pigs, which is the source of most available data (Yang et al., 1997; Salt et al., 1998; Sellers, 1971). These data made it possible to quantify the FMD transmission between pigs and to estimate the efficacy of vaccination.

2.2 Control strategies

The size and duration of an epidemic depend largely on the control strategy implemented and on its effectiveness. In 1990/91 the EU decided to cease routine prophylactic vaccination. The control procedures are now total stamping out[1] of the disease in affected herds and movement control[2] in the surrounding area. These measures are laid down in Council directive 85/511/EEC. However, in certain circumstances these measures may need to be supplemented by other interventions like ring culling[3] or ring vaccination[4]. In particular, outbreaks in areas containing high densities of susceptible animals and inadequate resources of manpower or plants for the slaughter and disposal of animals may spread out of control without additional control measures. In this context, ring culling and ring vaccination strategies target infection hotspots by reducing the density of susceptible herds in the vicinity of diagnosed infections, thereby removing the "fuel" essential to maintaining the epidemic (Scientific Committee on Animal Health and Animal Welfare, 1999; Ferguson et al., 2001a).
Findings from simulated FMD outbreaks in the Netherlands, Australia and France demonstrated that the strategy of stamping out and movement control alone (as laid down in 85/511/EEC) is almost never the economically optimal strategy. Extension of this strategy with culling of dangerous contact herds[5] generally reduced the epidemiological and economic consequences (Berentsen et al., 1990; Garner et al., 1995; Mahul et al., 2000).
Previous research based on the Dutch classical swine fever (CSF) epidemic of 1997-1998 showed that ring culling can also be an effective strategy to reduce the size of a CSF epidemic, if started in an early stage (Nielen et al., 1999; Elbers et al., 1998, Stegeman et al., 1999). These studies suggested that 1 kilometre was an optimal radius from an epidemiological as well as an economic point of view. A model analysis of the recent FMD epidemic in Great Britain (GB) showed that both ring culling and ring vaccination are potentially highly effective strategies if implemented sufficiently rigorously (Ferguson et al., 2001a). Also was concluded that ring vaccination policies need to be more extensive than comparable culling policies. In the case of infected but undiagnosed animals culling eliminates virus replication by removing these animals. Vaccination only reduces the virus replication thereby limiting the transmission of the virus less than culling (Sobrino et al., 2001). Another analysis of the GB epidemic (Donaldson et al., 2001) concluded that ring culling is not always effective because of the very wide variation between different species in terms of the quantities of virus excreted, their susceptibility to infections, and the routes by which they are likely to be infected.

Based on the current EU legislation and previously discussed experiments and analyses of recent epidemics the following interesting control strategies were considered in this study:
(1) stamping-out of infected herds (85/511/EEC) and culling of high-risk contact herds (SO);

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[1] slaughtering of all the affected and in-contact susceptible animals on the infected herd
[2] prohibition of movement of animals and manure within a radius of 10 km of an infected herd
[3] slaughtering all susceptible animals within a certain radius of every newly diagnosed case of infection
[4] vaccinating all susceptible animals within a certain radius of every newly diagnosed case of infection
[5] slaughtering of herds that, although not showing FMD symptoms, are considered to be at high risk of spreading the disease because of proximity or contact with infected herds.

(2) SO extended with ring culling of all susceptible animals within a radius of 1 km of an infected herd (RC1);
(3) SO extended with ring vaccination of all susceptible animals within a radius of 1 km of an infected herd (RV1);
(4) SO extended with ring vaccination of all susceptible animals within a radius of 3 km (RV3).

All four strategies include movement control. The last three strategies also took into account the possibility of airborne spread outside implemented rings. Susceptible animals outside a ring but downwind a virus plume were respectively culled or vaccinated. Vaccinated animals became culled as quickly as possible to keep the necessary period for regaining the status of FMD-free country without vaccination as short as possible (see 2.5). Here, culling and destruction capacities were the restricted factors.

2.3 Regions

Studies have shown that a densely populated livestock area (DPLA) can give rise to the risk of major disease epidemics (Dijkhuizen et al., 1995). For this study the Netherlands has been divided into seven regions according the division method of Stegeman et al. (1997) based on pig density per municipality. This method was useful for the epidemiological module, which calculated the transmission of a pig-adapted FMDV strain (see 2.1). Statistics were used of the year 1999 and pig densities are based on agricultural land area (Statistics Netherlands, 2001). According to this method, municipalities with more than 1000 pigs per km^2 were combined to form a pig-dense region. Municipalities that have fewer than 1000 pigs per km^2, but that are surrounded by densely populated municipalities were included in the pig-dense regions. Figure 2 shows the seven regions that could be distinguished. The very dark-coloured regions (regions 1, 2 and 3) have more than 1000 pigs per km^2. The other four areas are less densely populated.

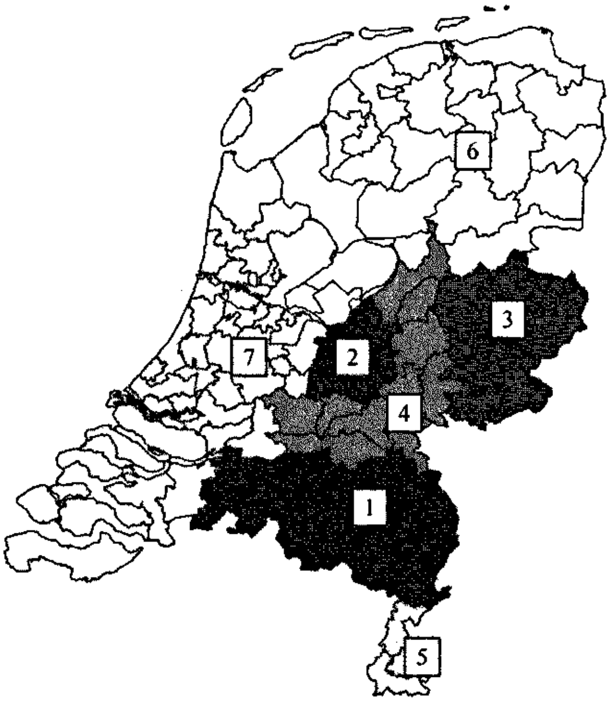

Figure 2. Subdivision of the Netherlands into seven regions

Table 1 lists the densities of susceptible livestock species, herds and flocks per region and the mean sizes of herds and flocks per region. According to the definition of Michel et al. (2000)[6] the regions 1 through 4 are classified as DPLAs.

Not only animal densities vary between regions but also the number of pig and cattle herds per squared km vary strongly. Region 2 has by far the most pig herds and cattle herds per squared km. In this region the mean size of pig herds is small but the mean size of cattle herds is large because of a high concentration of veal calves in this area.

Table 1
Descriptive statistics for the regions

	Region	1	2	3	4	5	6	7
Total livestock per:								
	km^2 agricultural land	3019	2641	1633	1353	563	389	384
	km^2 total land	1272	701	920	615	275	236	148
Pigs:	Pigs/km^{2*}	2691	1736	1290	916	346	152	175
	Herds/km^{2*}	2.30	4.56	2.32	1.24	0.41	0.19	0.31
	Herd size	1171	381	555	738	851	798	559
Cattle	Cattle/km^{2*}	279	838	305	336	166	178	129
	Herds/km^{2*}	3.28	7.29	4.69	4.42	2.72	2.05	2.05
	Herd size	85	115	65	76	61	87	63
Sheep	Sheep/km^{2*}	30	47	31	84	42	55	76
	Flocks/km^{2*}	1.11	2.24	1.48	2.55	1.56	1.20	1.77
	Flock size	27	21	21	33	27	46	43
Goats	Goats/km^{2*}	19	19	7	16	10	4	5
	Flocks/km^{2*}	0.22	0.41	0.35	0.55	0.15	0.31	0.30
	Flock size	85	46	20	29	65	13	15

* per km^2 agricultural land

2.4 Scenarios

Scenarios were defined by important determinants in the development of epidemics that were found in literature. These determinants were: (a) livestock and herd density in the outbreak region (De Vos et al., 2000; Gerbier, 1999), (b) the possibility of airborne spread (Donaldson et al., 2001), and (c) the high-risk period (HRP) which is defined as the time interval between first infection and first detection (Horst, 1998). In figure 3 each scenario is described by a region (which was described by livestock density and herd density), the possibility of airborne spread and the HRP.

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[6] A DPLA for FMD contains >300 pigs per km^2 or >450 susceptible animals per km^2 (total land area).

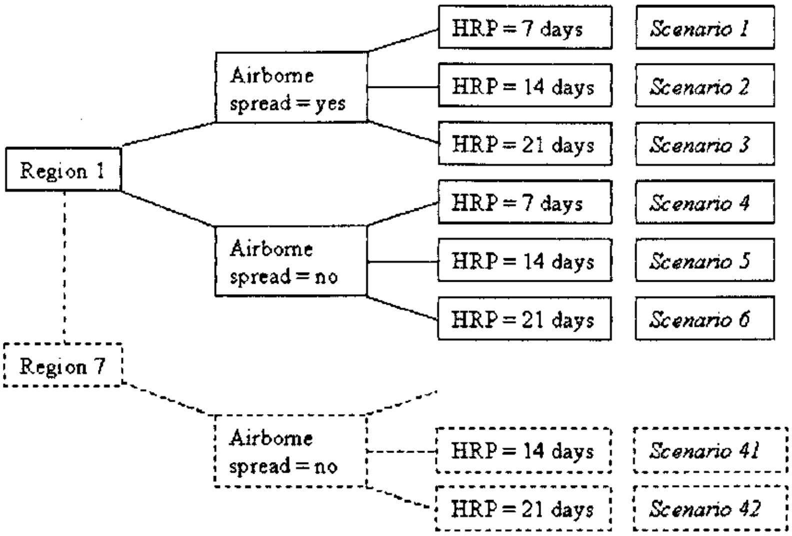

Figure 3. Scenarios in the module

2.5 Epidemiological module

A mathematical model was constructed to estimate the effect of control strategies in the separate regions. A previously described deterministic SIR model (De Jong, 1995; Stegeman et al., 1999) was applied to describe the transmission of FMDV between herds. In this model, S is the number of susceptible herds, I the number of infectious herds and R the number of recovered herds. Because herds are depopulated upon detection, R = 0 at all times in this study. In the model, the rate at which susceptible herds become infected can be described as: $C = \beta * SI/N$, in which C is defined as the number of virus introductions per unit of time into a susceptible herd, β as the infection-rate parameter and N as the total number of herds. Furthermore, infected herds are depopulated at the rate $D = \alpha * I$, in which D is defined as the number of infected herds depopulated per unit of time and α as the depopulation-rate parameter. The parameter α is the inverse of T, the average period that a herd is infectious. The transmission of FMDV between herds can be expressed as the herd reproduction ratio R_h, which is defined as the average number of outbreaks caused by one intial infected herd. The R_h can be estimated from $R_h = \beta / \alpha$ (Stegeman et al., 1999). From the definition of R_h it follows that if R_h is <1, the epidemic will fade out automatically. On the other hand, if R_h is >1, the virus will continue to spread (De Jong, 1995; Diekmann et al., 2000).
Knowledge and factual information on the precise transmission routes of FMD are scarce. This is in contrast to CSF (for example see Stegeman et al., 1999 & De Vos et al., in press). Both diseases are list A diseases and approximately spread via the same transmission routes (De Vos et al., in press; Elbers et al., 1999; Donaldson et al., 2001). Therefore, to estimate the R_h, data collected during the Dutch CSF epidemic in 1997-1998 was used (Stegeman et al., 1999). Five transmission routes were distinguished by which the virus could be transmitted from one herd to another: animal transport, persons, neighbourhood, artificial insemination (AI), and rendering (Stegeman et al., 2000; Elbers et al., 1999). Three types of herds were defined: breeding herds, farrow-to-finish herds and finishing herds. The infectiousness of a herd was determined by the virus transmission within the herd (Van Nes et al., 1998). The parameters were adjusted to FMD using collected data from recent FMD outbreaks and data from transmission experiments (Yang et al., 1997; Salt et al., 1998; Sellers, 1971).
For each transmission route a transmission matrix was composed to model the transmission from one herd type to another (Stegeman et al., 2000). These matrices combined the number of contacts and the estimated chance of transmission by a contact. The values in the transmission matrices were made dependent on herd density and mean herd size in the

concerning outbreak region, as previously applied in ADV and CSF control studies (Koeijer et al., 2000; Stegeman et al., 2000).
Because the transmission routes were independent of each other, the five matrices could be added to one total transmission matrix. Subsequently the R_h was determined by calculating the dominant eigenvalue of the matrix. The matching eigenvector reflects the proportion of each herd type that got infected (Diekmann et al., 2000). The R_h was determined for each control strategy and each region. In the case of ring vaccination the assumption was made that transmission continued during one week after vaccination and after that transmission stopped in vaccinated herds. The model was programmed in Mathematica 4.0 (Wolfram Research).
Main difference between transmission routes of FMD and CSF is that FMD virus could be spread by wind over long distances under certain weather circumstances[7] (Gloster et al., 1982; Donaldson et al., 2001), although opinions differ about the range of airborne spread. Air currents play a minor role as a transmission route between herds for CSF (De Vos et al, in press; Elbers et al., 1999). Therefore, airborne transmission was calculated separately, and was subsequently added to the R_h for the scenarios with airborne spread. (Gloster et al., 1982) For each combination of control strategy and region a worst case of airborne spread was modelled (Gloster et al., 1981).
The calculated herd reproduction ratios were used to derive number of herds affected, duration of epidemics and areas subjected to movement restrictions for the defined scenarios (see section 2.4). These outputs were used as inputs to the economic module (see figure 1).

2.6 Economic module

The purpose of the economic module was to quantify payoffs that then could be used in the decision tree module as the economic consequences of control strategies (see 2.7). Payoffs were defined as the direct costs and the consequential export losses of spread and control of an FMD epidemic. The direct costs were defined as the economic implications for (1) producers in the entire livestock value chain whose income depends on the livestock sector (e.g. farmers, abattoirs, hauliers and meat processors) and for (2) the government who is organising the disease control. Direct costs are generated by the implementation of control measures, such as costs of animal slaughter and vaccination, compensation payments and costs due to movement restrictions and idle production factors (Berentsen et al., 1990). An epidemic could also have consequential export losses (Berentsen et al., 1990; Garner et al., 1995; Mahul et al., 2000). These losses were defined as the value of livestock and livestock products that could not be exported because of trade restrictions due to the FMD epidemic.
In this module, the direct costs and consequential export losses were calculated in a rather objective way using several statistical databases (Statistics Netherlands, 2001; Product Boards for Livestock, Meat and Eggs, 2000; Product Board for Dairy, 2000). The module was programmed in Excel 97 (Microsoft Corporation).

2.6.1 Input data for direct costs

The economic module used the outputs from the epidemiological module (see figure 1). To calculate the direct costs it used the number of affected herds, the duration of epidemics and the size of areas subjected to movement restrictions. The number of culled or vaccinated animals were calculated. These calculations were based on livestock and herd densities in the outbreak region and the estimated number of contact herds, based on the calculated R_h, during the period between first infection and first detection. The duration of epidemics was increased when the culling and rendering capacity was not sufficient. The culling and rendering capacity was set at 16 farms per day for the SO and RC1 strategies and at 36 farms per day for the RV1 and RV3 strategies.

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[7] Most favourable conditions for airborne spread are a constant wind direction, a wind speed of 5 m/second, a high atmospheric stability, no precipitation, and a relative humidity above 55 % (Donaldson et al, 2001).

For each scenario the direct costs were calculated as costs per dairy cow, sow or fattening pig that was culled or put under movement restrictions. Input values to calculate the direct costs are represented in table 2. These values were calculated on base of statistics of the Agricultural Information and Knowledge Centre and Research Station for Animal Husbandry (2000) and estimates of the National Inspection Service for Livestock and Meat (Meuwissen et al., 1999). Organisation costs refer to costs of diagnosis, valuation of the animals, killing, cleansing and disinfection of stables and equipment and surveillance in the protection and surveillance zones. Compensation payments are governmental payments to farmers whose animals were culled. These payments were calculated as the replacement values of the animals and present feed. Costs from idle production factors were calculated as the fixed costs decreased by released labour that could have been deployed elsewhere. The costs of movement restrictions were calculated as the costs for additional feed for maintenance and other supply and delivery problems because of the restrictions. Vaccination costs include labour and material costs of the vaccination teams (Mangen et al., 2001). For sheep and goats only the replacement values were included because a large part of these animals are kept as hobby animals.
The losses for supplying, processing and distribution companies were calculated as half of the the gross value added of agricultural production that did not take place due to the implemented control strategies. The distribution of the gross value added within the livestock production chain is shown in appendix I (Koole et al., 2000).

Table 2
Input values for calculating the direct costs per dairy cow, sow and fattening pig (in €)

	Dairy cow (incl. young stock)	Sow (incl. piglets)	Fattening pig
Organisation costs	136	68	18
Compensation payments	1190	349	66
Idle production factors	4.95/day	0.66/day	0.14/day
Movement restrictions	0.07/day	0.15/day	0.02/day
Vaccination costs	9	7	2

2.6.2 Input data for consequential export losses
The extent of the consequential export losses depends on the duration and size of the epidemic and the reactions of importing countries during and after the epidemic. The studies of Mahul et al. (2000) and Berentsen et al. (1990) showed that import bans implemented by the importing countries play a key role in the evaluation of economic consequences of an FMD epidemic. The duration and size of the epidemic resulted from the epidemiological module. For the possible reactions of importing countries two scripts were formulated. One script was based on OIE guidelines (see table 3a).

Table 3a
Import bans during and after an FMD epidemic in the OIE-script (OIE)

		During epidemic	After epidemic (days)	
			Regional	National
EU	Livestock	national	90	n.a.[1]
	Meat	regional	90	n.a.
	Dairy products	regional	0	n.a.
Non-EU	Livestock	national	90	n.a.
	Meat	regional	90	n.a.
	Dairy products	regional	0	n.a.

[1] Not applicable

According to the OIE International Animal Health Code countries recover their status of FMD-free zone without vaccination after: (i) 3 months after slaughtering of the last infected herd when there is no vaccination strategy implemented but only stamping out and preventive slaughter or (ii) 3 months after slaughtering of the last vaccinated herd if a campaign of emergency vaccination is applied (Office International des Epizooties, 2000).

However, reactions of importing countries during and after epidemics in the past proved that these countries did not respect the OIE guidelines. For this reason, a more realistic script (REA) was based on international trade restrictions applied during epidemics in the past (e.g. Italy, 1993; Greece, 1994; Great Britain & The Netherlands, 2001). The assumed import bans are mentioned in table 3b. Assumptions on the duration of import bans were based on results of previous studies of Berentsen et al. (1990) and Mahul et al. (2000) and experiences of recent outbreaks (Commission Decisions 2001/172/EC and 2001/223/EC).

Table 3b
Import bans during and after an FMD epidemic in the more realistic script (REA)

		During epidemic	After epidemic (days)	
			Regional	National
EU	Livestock	national	180	n.a.[1]
	Meat	regional	180	n.a.
	Dairy products	regional	0	n.a.
Non-EU	Livestock	national	n.a.	360
	Meat	national	n.a.	360
	Dairy products	regional	90	n.a.

[1] Not applicable

In both scripts three export product groups were distinguished: (1) livestock, (2) meat products and (3) dairy products. The importing countries were divided in a group of EU-countries and non-EU countries. Next, for each combination of product group and country group was determined how long an import ban was effective and whether the ban was at a national or regional level. A regional import ban means an import ban for products coming from regions around infected farms in radii of 10 km. Because regional export data were not available, the assumption was made that exports were proportional to the regional production (Mahul et al., 2000)

2.7 Decision tree module

Rational economic decision making models assume perfect markets and perfect information (Mileti, 1999). But in reality animal health authorities are faced with sparse information about the probable efficacy of proposed control strategies. A decision tree analysis offers a formal, structured approach to decision-making, taking into account elements of uncertainty (Marsh, 1999). The aim is to make explicit the chronological decision process and to arrive at the best decision given the available information.

In this study the objective of the decision tree was to optimise early decisions to control FMD epidemics by calculating the economically optimal control strategy. A multi-attribute decision tree was built using the expected value criterion (Winterfeldt et al., 1986). The two attributes were the direct costs and the consequential export losses and were weighted equally. For each scenario (see figure 3) these attributes were calculated by means of the epidemiological and economic module.

In the early stages of a possible epidemic information is available on the outbreak region (livestock density and herd density) and the possibility of airborne spread (weather conditions). Information on the high risk period (HRP) is often sparse, because the source of introduction of FMDV in the primary-outbreak herd is often unknown and the analysis of virological and serological samples takes time (Horst, 1998). The decision tree method is used in two different situations: (1) if the HRP is known (see figure 4a), and (2) if the HRP is unknown (see figure

4b). In this last situation the probabilities of the HRP-s were weighted equally. The trees were built in Data 3.5 (TreeAge Software, Inc.)

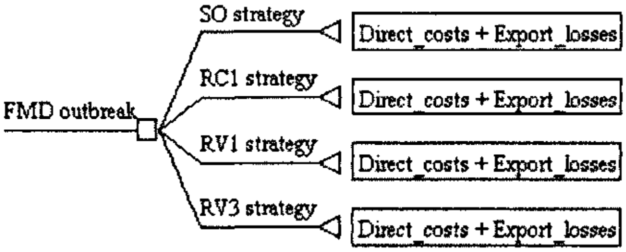

Figure 4a Decision tree if the HRP is known

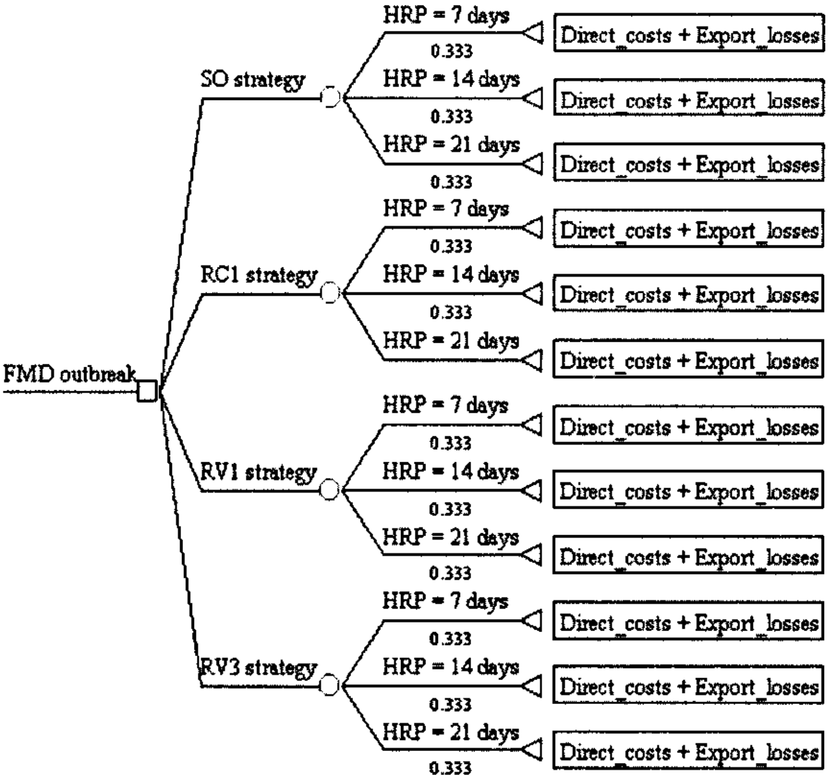

Figure 4b Decision tree if HRP is unknown

3. Results

The epidemiological module simulated the disease dynamics, the economic module converted outbreak and control effects into estimates of direct costs and export losses, and finally a decision tree module optimised decisions on control strategies.

3.1 Epidemiological results

The epidemiological module generated the herd reproduction ratios (R_h) for each combination of region, control strategy and the possibility of airborne spread (see table 4). When the R_h <1, exact numbers are not shown because the epidemic will fade out automatically. The results indicate that the SO-strategy is not adequate to stop the epidemic in the regions 1, 2, 3 and 4 in the scenarios with airborne spread because the R_h is >1. Additional measures are necessary. In the other three regions the SO-strategy eradicates the virus because R_h is <1. With additional measures the R_h could be reduced and likewise the number of infected farms and the duration of the epidemic. In case of airborne spread, the RC1-strategy is also not very effective in region 2 because of the high livestock and herd densities and the limited culling capacity. Ring vaccination is then the only option in this region to eradicate the virus.

Table 4

R_h for each region, control strategy and the possibility of airborne spread

	Region	1	2	3	4	5	6	7
Without control		5.8	3.9	4.0	3.9	4.4	3.2	4.0
SO	airborne spread	2.0	2.7	1.7	1.1	<1	<1	<1
	no airborne spread	1.0	1.0	<1	<1	<1	<1	<1
RC1	airborne spread	<1	1.0	<1	<1	<1	<1	<1
	no airborne spread	<1	<1	<1	<1	<1	<1	<1
RV1	airborne spread	<1	<1	<1	<1	<1	<1	<1
	no airborne spread	<1	<1	<1	<1	<1	<1	<1
RV3	airborne spread	<1	<1	<1	<1	<1	<1	<1
	no airborne spread	<1	<1	<1	<1	<1	<1	<1

3.2 Economic results

The economic module calculated 336 times (42 scenarios per region * 4 control strategies * 2 scripts for possible import bans) the direct costs and consequential export losses of an FMD epidemic. To give an indication of the major results, the extremes in sizes and economic consequences within these 336 calculations are presented in table 5.

In the regions 1, 2, 3 and 4 the epidemic becomes endemic in the worst case scenarios. These results also indicate that the export losses are much higher than the direct costs. This is valid for both scripts, although export losses in the OIE-script were lower than in the REA-script.

Table 5

Extremes in sizes and economic consequences of FMD epidemics in each region

Region		1	2	3	4	5	6	7
Duration (days)	Min	75	72	54	46	47	41	45
	Max	end.[1]	end.	end.	end.	180	123	119
No. infected herds	Min	11	8	7	6	6	4	5
	Max	end.	end.	end.	end.	494	159	245
Movement control surface (km^2)	Min	518	483	432	411	416	393	407
	Max	end.	end.	end.	end.	10874	1500	2066
Direct costs (in million €)	Min	83	60	36	24	16	4	5
	Max	end.	end.	end.	end.	1478	63	110
Export losses (REA) (in million €)	Min	563	443	453	407	314	315	339
	Max	end.	end.	end.	end.	3051	678	926
Export losses (OIE) (in million €)	Min	255	183	179	144	90	81	99
	Max	end.	end.	end.	end.	2305	389	573

[1] end. = the epidemic became endemic (duration > 1 year)

3.3 Results decision trees

The decision tree module was used in two different situations: (1) if the HRP is known and (2) if the HRP is unknown (see figures 4a and 4b).

3.3.1 *If HRP is known*

The economically optimal and next to optimal control strategies for each region and HRP are shown in table 6a (with airborne spread) and table 6b (without airborne spread). These tables also present the costs + losses and is defined as the difference in direct costs and export losses between the optimal strategy and the next to optimal strategy.

Table 6a
Optimal and next to optimal control strategies and the differences in costs and losses (in million €) between these strategies in the scenarios with airborne spread

Region	1	2	3	4	5	6	7
HRP = 7							
optimal strategy	RV3	RV3	RV1	RC1	RC1	RC1	RC1
next to opt. strategy	RV1	RV1	RV3	RV1	RV1	RV1*	RV1*
costs + losses (REA)	51	11	5	61	35	49	49
costs + losses (OIE)	35	9	3	52	32	45	44
HRP = 14							
optimal strategy	RV1	RV3	RV3	RC1	RC1	RC1	RC1
next to opt. strategy	RV3	RV1	RV1	RV1	RV1	RV3	RV1
costs + losses (REA)	30	55	176	24	14	51	47
costs + losses (OIE)	29	44	134	20	13	46	41
HRP = 21							
optimal strategy	RV1	RV3	RV1	RV3	RV1	RC1	RC1
next to opt. strategy	RV3	RV1	RV3	RV1	RV3	RV1	RV3
costs + losses (REA)	405	766	241	90	5	134	61
costs + losses (OIE)	404	746	236	71	3	62	51

*OIE-script: SO

Table 6b
Optimal and next to optimal control strategies and the differences in costs and losses (in million €) between these strategies in the scenarios without airborne spread

Region	1	2	3	4	5	6	7
HRP = 7							
optimal strategy	RV1	RV1	RC1	RC1	RC1	RC1	RC1
next to opt. strategy	RV3	RV3	RV1	SO	SO	SO	SO
costs + losses (REA)	7	10	51	46	24	14	24
costs + losses (OIE)	5	7	42	33	20	11	39
HRP = 14							
optimal strategy	RV1	RV1	RV1	RC1	RC1	RC1	RC1
next to opt. strategy	RV3	RV3	RV3	RV1	RV1	SO	RV1
costs + losses (REA)	31	34	9	73	26	30	51
costs + losses (OIE)	28	32	7	61	21	25	45
HRP = 21							
optimal strategy	RV1	RV3	RV1	RV3	RV1	RC1	RC1
next to opt. strategy	RV3	RV1	RV3	RV1*	RV3	SO	RV3
costs + losses (REA)	259	471	96	83	9	62	90
costs + losses (OIE)	219	451	33	63	6	48	76

* OIE-script: RC1

These tables show that ring vaccination is always be the economically optimal strategy in regions 1 and 2. The optimal radius of the ring vaccination depends on the length of the HRP. Ring culling is always the economically optimal strategy in regions 6 and 7. For the regions 3, 4 and 5 the economically optimal strategy depends on the length of the HRP and the presence of airborne spread.

The results of the two scripts of possible reactions of importing countries show almost the same rankings of economically optimal and next to optimal strategies. The differences in costs and losses between the economically optimal and next to optimal strategy generally increase as the HRP is stretched out.

3.3.2 If HRP is unknown

The economically optimal and next to optimal control strategies for each region when the HRP is unknown are shown in table 7. Ring vaccination is always the optimal strategy in the regions 1, 2 and 3 because ring vaccination reduces the number of infected herds and the duration of the epidemic.

Table 7
Optimal and next to optimal control strategies and the differences in costs and losses (in million €) between these strategies

Region	1	2	3	4	5	6	7
Airborne spread:							
optimal strategy	RV1	RV3	RV1	RV3	RV1	RC1	RC1
next to opt. strategy	RV3	RV1	RV3	RV1	RV3	RV3	RV3
costs + losses (REA)	128	268	23	25	4	81	56
costs + losses (OIE)	132	256	38	21	1	69	48
No airborne spread:							
optimal strategy	RV1	RV3	RV1	RC1	RC1	RC1	RC1
next to opt. strategy	RV3	RV1	RV3	RV3*	RV1	RV3	RV3
costs + losses (REA)	94	142	28	13	7	65	66
costs + losses (OIE)	110	12	7	42	8	57	56

*OIE-script: RV1

Ring culling is always the optimal strategy in the regions 6 and 7. In these regions, ring vaccination prolongs the epidemic and enlarges the surface of movement standstill areas. For regions 4 and 5 the optimal strategy depends on the presence of airborne spread.
The results of the two scripts of possible reactions of importing countries show almost the same rankings of optimal and next to optimal strategies.

4. Discussion

4.1 Epidemiological module

This study used available knowledge to model the epidemiological and economic consequences of an outbreak. Because of this reason, the model was restricted to a pig-adapted FMD virus strain. There was not much knowledge available on virus transmission in the field between other susceptible animals. This means that the results can only be interpreted as the optimal strategies for pig-adapted FMD virus strains.

4.2 Economic module

The economic module converted outbreak and control effects into estimates of direct costs and consequential export losses for producers in the livestock value chain and the government. An epidemic could also have effects on the Dutch economy as a whole because of side effects of disease control measures (e.g. the closure of footpaths harms the tourist sector) and interactions between economic sectors (e.g. price drops for livestock products favours consumers) (Berentsen et al., 1992; Mahul et al., 2000; Gardner et al., 1995). These 'non-agricultural' effects have not been quantified because it was not the aim to carry out a full social cost-benefit analysis (CBA). CBA provides a framework for comparing disease control strategies but includes also difficulties. Many costs and benefits are by their nature non-measurable (e.g. emotional problems of farmers whose animals had to be culled).

Assigning monetary values to these costs and benefits is a major problem of CBA and involves making subjective judgements (Ramsay et al., 1999).
A knowledge gap was found in the possible reactions of importing countries. Reactions do not always respect the OIE guidelines. This problem was solved by using two scripts for possible reactions. The model showed that varying lengths of import bans had limited influence on the economically optimal control strategies. A limitation of the calculations is that these were based on changes in quantities due import bans. Price and substitution effects were excluded in the economic calculations.

5. Conclusions

The decision tree is a useful tool to optimise early decisions to control FMD epidemics in different regions in the Netherlands. The outcomes can be used as yardsticks for deciding on control measures during possible FMD epidemics in the future. The results showed that not selecting the economically optimal strategy may cause large additional economic losses. Animal density within the outbreak region is an important determinant in deciding on the optimal control strategy. The results show a considerable regional variation in the size of impacts. Ring vaccination is the economically optimal strategy for densely populated livestock areas because this strategy reduces the number of infected herds and the duration of the epidemic compared to the other strategies. Ring culling is the economically optimal strategy for sparsely populated livestock areas. For livestock areas that are neither very densely populated nor very sparsely populated, the optimal strategy depends on the length of the HRP and the presence of airborne spread.
The duration of an epidemic was one of the most important parameters, which determined the economic impact of an epidemic. This was consistent with previous research (Horst et al., 1999; Mahul et al., 2000). In densely populated livestock areas the culling and rendering capacity was the limiting factor causing delays in culling and extension of the epidemic. Therefore, ring vaccination is the optimal strategy in these areas because it reduces the number of infected farms and likewise the duration of the epidemic.
The decision tree approach was also very useful because it offers the opportunity to use new information during the process of decision-making (Hardaker et al., 1997; Winston, 1991). The results study emphasizes the importance of retrieving information on the length of the HRP as soon as possible after an outbreak of FMD has been decleared.

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Appendix I

Table 1
Distribution of the gross value added (in billion €) within the livestock production chain (mean value of 1995 and 1998)

	Grassland based livestock farming		Intensive livestock farming		Total	
	billion €	%	billion €	%	billion €	%
Livestock farms	3.0	41	0.7	22	3.7	35
Supply industry	1.4	19	0.7	22	2.1	20
Processing industry	2.2	30	1.3	40	3.5	33
Distribution industry	0.7	10	0.5	16	1.2	12
Total	7.3	100 %	3.1	100 %	10.5	100 %